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A QUANTITATIVE STUDY OF ACHROMATIC AND CHROMATIC SENSITIVITY FROM CENTER TO PERIPHERY OF THE VISUAL FIELD

By

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PREFACE

The subject of this dissertation was suggested by Dr. C. E. Ferree, sometime Professor of Experimental Psychology at Bryn Mawr College, now Director of the Research Laboratory of Physiological Optics of the Wilmer Ophthalmological Institute, Johns Hopkins University Medical School. The dissertation was prepared under his direction. The writer wishes to acknowledge her indebtedness to Dr. Ferree for the suggestion of the problem and to both Dr. Ferree and Dr. Rand for the time and effort which they have given to supervision of the work on the dissertation. She wishes also to express her appreciation to Dr. Rand for her many valuable suggestions with reference to the experimental method and for her kindness in making all the energy measurements required and in determining the peripheral refraction of the eye used in the investigation. Acknowledgment is also made to Dr. Alfred Cowan for his assistance in the ophthalmoscopic examination and photography of the retina.

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I. INTRODUCTION

The sensitivity of the retina to color, both central and peripheral, has been a subject of continual interest during the past century, not only in relation to theoretical problems of physiology and psychology, but also in connection with the whole field and program of testing the visual response. It is the latter connection which is of particular interest and importance at the present time. Disturbances of the visual functions, particularly of the light and color sense of the peripheral retina, bear a close relationship to serious affections not only of the eye, but of the entire optic system: nerve, chiasm, optic tract and radiations, and visual centers; and of those portions of the brain adjacent to these structures. These disturbances are of particular significance in the field of medicine, since functional disturbances, as a rule, precede detectable structural changes in the fundus, while pathologic conditions back of the globe of a kind or magnitude which produce no objective changes in the fundus may be detected, very often at an early stage, through variations in the visual response.

The visual response is subject to the influence of many factors. Some of these are amenable to experimental control, others must be dealt with by statistical procedure. To the former class belong the factors which cause variability of result in a given eye; to the latter those which cause results to differ from eye to eye. In addition there is an inherent selectiveness of reaction to the influence of any factor. The failure to control the influence of variable factors and the lack of knowledge of the inherent selectiveness of response to any given factor when varied under control have led not only to erratic results but to incorrect interpretations and conclusions with regard to the results which have been obtained. The important practices of perimetry and scotometry have been for many years all but abandoned in spite of their acknowledged value for the detection of the presence and

in the study of the progress of pathological conditions, because of the great difficulty encountered in obtaining reliable results and the confusion that has arisen in the interpretation of these results. It has become highly important, therefore, that detailed studies be made not only of the factors which influence the visual response but of the characteristics and peculiarities of this response under precise conditions of control if a sound basis is to be laid upon which to build explanatory theories, and if the true significance of the determinations of the sensitivity of the retina to light and color in relation to pathological conditions of the eye and the brain is to be discovered and reproducible results obtained. This knowledge of characteristics and controls is needed also in adapting light to the best service of the eye in problems of illumination; in the correct use of the eye in the various scientific and technical ways in which it is employed; in rating light intensities in photometry, in colorimetry, etc.; in tests for vocational fitness; and in many other practical applications of physiological optics.

A great deal of work along these lines has been conducted in the laboratory of psychology at Bryn Mawr College. The program of work has included (a) a detailed study of the factors which influence the various types of visual response; (b) the devising of methods and apparatus for controlling and standardizing the influence of these factors and for testing and rating the response in terms which are numerically comparable; and (c) a study of the responses in all parts of the retina and the extension of the methods devised and the knowledge obtained to the various fields of applied physiological optics.

The present study is a continuation and extension of an investigation begun by Ferree and Rand in 1915.(1) The purpose of their investigation was a minute study of the chromatic sensitivity of the retina from center to periphery in a number of meridians sufficiently great to provide a comprehensive and representative knowledge of the irregularities and characteristics of the distribution of sensitivity in the visual field. The work was interrupted, however, when the survey had been made only in the

temporal and nasal quadrants of the horizontal meridian[1] under light adaptation. In the present study the survey of the distribution of chromatic sensitivity under light adaptation has been completed and, in addition, a study has been made under dark adaptation of both the chromatic and achromatic sensitivity of the retina, and of the photochromatic interval, at near-lying points from center to periphery in a number of meridians.

The study of sensitivity has been made by the threshold method. Spectrum lights have been used and the intensity of the light required just to arouse the chromatic and achromatic sensation has been measured in energy terms. The results obtained have thus been made as nearly as possible quantitative and absolute. The value of the photochromatic interval at the various points under investigation has also been expressed in energy terms.

[1] In the use of the term quadrant of the meridian or meridional quadrant instead of meridian in this and the following sections, the writer is following a recommendation made by Ferree, Rand and Monroe (Studies in Perimetry: 2, Preliminary work on a diagnostic scale for the color fields. *Amer. J. Ophth.*, 1929, **12**, 269–285; Studies in Perimetry: 3, Errors of refraction, age and sex in relation to size of form field, *Amer. J. Ophth.*, **12**, 659–664; Errors of refraction, age and sex in relation to the size of the form field and preliminary data for a diagnostic scale, *Bull. of the Johns Hopkins Hospital*, 1929, 45, 295–314). In support of the need for a change in terminology, they say: "As in former papers, the term meridian is used here for the quadrant of the meridian. While it is not necessary in refraction to treat of the two anterior quadrants of the meridian separately, there is need for the separate treatment in perimetry.

"Since the situation and needs in perimetry and refraction are so different, there seems intrinsically to be no good reason why the same designation should be used in the two cases. It might be advisable and convenient in perimetry to adopt the term quadrant and to number the quadrants for the right eye counterclockwise from 0, right horizontal, to but not including 360 degrees; and for the left eye clockwise from 0, left horizontal, to but not including 360 degrees. By this method the quadrant designations would correspond throughout for the two eyes, *i.e.*, 45 degrees would represent upper temporal, 135 degrees upper nasal, and so on, for both eyes; but two sets of maps would be required, one for the right eye and one for the left. Similarly two concentric sets of graduations would be needed on the dial of the perimeter, one numbered clockwise for the right eye, the other counterclockwise for the left eye."

The writer wishes to point out, however, that the term quadrant has become so firmly intrenched in the perimetric literature as referring solely to the field quadrant, *i.e.*, to a quarter section of the entire field, that confusion will inevitably result unless a very clear differentiation is made between the meridional and the field quadrants.

Although the main purpose of the study has been to give a picture of the actual distribution of sensitivities that is found at points selected as representative of the entire surface of the retina, the investigation has an additional value in serving to clear up certain misconceptions that have been held as to the color sensitivity of the peripheral retina. These misconceptions have had an important bearing on the formulation of certain types of color theory and on the clinical applications of the study of sensitivity.

In relation to those misconceptions which have had an important bearing on color theory, the investigation is chiefly of value in corroborating the findings of Ferree and Rand, and in confirming the inferences as to the distribution of sensitivity over the entire surface of the retina which they have drawn from their less extensive investigation. The relation of their work to color theory was published in 1919 (2) and need not be summarized here.

The clinical application of the study of sensitivity may for convenience of treatment be divided into two classes; the study of central sensitivity and the study of paracentral and peripheral sensitivity. The advantages of the study of central sensitivity may be summarized as follows:

(a) From the standpoint of experimental controls and variation and of measurement, the test of central sensitivity is easier to make. Also the conditions are more favorable from the standpoint of the judgment and responses of the observer.

(b) The ocular functions are more highly developed, more numerous, and in general more sensitive to pathological disturbances in the central than in the peripheral portions of the retina. There is, for example, a wide range of response for the light and color sense, for acuity, and for all the subsidiary functions in the central portions of the retina. These shade off to zero at the periphery. There is also a wider range and slower progress of adaptation at the center. In the periphery adaptation is of a very limited range, *i.e.*, the peripheral retina is in a permanent state

of partial dark adaptation. Adaptation is a very important and prominent function from the standpoint of diagnosis.

There are, however, important needs for testing in the paracentral and peripheral field. Among these may be mentioned the regional disturbances that characterize many of the ocular diseases. These diseases produce functional changes in the paracentral and peripheral portions of the retina alone or at least more changes there than in the central retina. Examples of these diseases are glaucoma; the ocular disturbances due to diseases of the sinus; papillitis and choked disc; optic neuritis and lesions along the optic nerve, chiasm, optic tract, the optic radiations and at the visual centers.

The study of paracentral and peripheral sensitivity by the threshold method may be conducted in three ways: (a) certain parts of the retina may be selected and the intensity varied until the threshold is reached; (b) a fixed intensity of stimulus may be used and a search made in the various meridional quadrants until a point is found in the field at which the stimulus is of threshold intensity; and (c) the field may be explored under fixed conditions of intensity and size of stimulus and relation to background for patches or areas showing sufficiently low sensitivity to be classed as pathological. The second of these methods is commonly known as perimetry, the third as scotometry. Because of the quickness and convenience of making the determinations, clinical studies have thus far been confined to these two methods.

If perimetry and scotometry are to be made of positive service in clinical work it is obvious that the following conditions must be satisfied: (a) means must be devised for obtaining reproducible results, *i.e.*, the variable factors which influence the results must be known and methods and instruments devised for their accurate control; (b) the range of variation which is apt to be found for non-pathological eyes under the best possible conditions of control must be determined; and (c) the misconceptions which are at present entertained must be corrected. The bearing of the present study is chiefly upon the first and third of these items. The construction of diagnostic scales or distribution curves to

serve as standards of reference in diagnosis and other forms of classification must be reserved for future work.[1]

At this point it will be sufficient to note some of the misconceptions that have been held with regard to the results that have been obtained by perimetry and to point out the bearing of the results obtained in our study on the problems presented by clinic perimetry.

(1) Certain changes in size, shape and order of ranking as to breadth of the color fields are generally considered to have pathological significance. According to the accepted clinic rating, for example, the normal color fields have concentric limits in order from widest to narrowest of blue, red and green. By many clinicians any change in this order of ranking, *e.g.*, an interlacing of limits or a complete reversal of order of ranking, is thought to have a pathological etiology. The results presented in this paper and, less extensively, those obtained by Ferree and Rand, show the following points:

(a) The peripheral retina is not blind to color. There are not fixed limits to the color fields which are changed only by pathology. By playing on the factors which influence the response of the retina to color, the apparent breadth of the fields may be made to vary from a few degrees to the breadth of the form field.

(b) The sensitivity to a given color falls off very irregularly in the various meridional quadrants from center to periphery of the retina. Any condition or factor, therefore, which changes the size of the non-pathological field may be expected also to change its shape.

(c) The ratio of sensitivity between any two colors varies greatly and irregularly from the center to the periphery of the retina in any given meridian. In passing from center to periphery at least one reversal of ratio may be expected for red, blue and

[1] See C. E. Ferree, Rand, G., and Monroe, M. M., Studies in Perimetry, I, Preliminary Work on a diagnostic scale for the form field. *Amer. J. Ophth.*, 1926, 9, 95–104; Studies in Perimetry, 2, Preliminary work on a diagnostic scale for the color fields, *Amer. J. Ophth.*, 1929, 12, 269–285; Errors of refraction, age and sex in relation to the size of the form field and preliminary data for a diagnostic scale. *Bull. of the Johns Hopkins Hospital*, 1929.

yellow. A normal corollary to extensive changes in size of field is, therefore, a reversal of order of ranking as to breadth. In the mid-region of the retina the reversals of ratio occur nearer the center in some meridional quadrants than in others. An interlacing of limits, therefore, characterizes these portions of the field. Changes in size, shape and order of ranking as to breadth of field, and an interlacing of limits may result, thus, from changes in the conditions under which the fields are taken.

(2) The presence of small patches or areas of insensitivity are usually considered to be of pathological origin. These are called scotomata and are classed as relative or absolute, depending upon the degree of insensitivity. An inspection of the sensitivity curves presented in this paper reveals, in places, dips which may be mistaken for relative scotomata. Small patches of absolute insensitivity to color are also frequently found in eyes which from all other recorded evidence are classed as non-pathological.

(3) The intensities of pigment stimuli commonly used in clinic practice are low as compared with those which may be obtained with spectrum light with the kind of apparatus used in this study. With the use of these weaker stimuli alone an examination cannot be made of the sensitivity of all parts of the retina. In this study we are able to obtain a comparison of the intensity of these stimuli with that required to arouse the chromatic response in the various parts of the retina and so to evaluate their usefulness for diagnostic testing.

(4) Dark-room perimetry with luminous test-objects has been suggested and strongly advocated at times as a substitute for light-room perimetry. The results obtained in this study show that adaptation is a very important factor in perimetry. Perimetry under dark and under light adaptation are very different subjects. It may be that the two conditions can be used to advantage in a supplementary capacity, but they cannot be used interchangeably. Dark-room perimetry may prove of distinct value as a special test. It has been claimed, for example, to be of particular service in the early detection of detachments of the retina. Not only is the eye a different organ under light and dark adaptation, but the process of adaptation is itself one of the most

delicate of the ocular functions and one liable to early and important changes as the result of pathology. We hope that the present investigation will lead to the further study of this process both as a factor and as a function in relation to the practical needs of the care and treatment of the eye.

A great deal must be known before knowledge can be made really useful. This is particularly true of the subjective methods of examination. They have many advantages, however, over the objective methods. Among these the following may be mentioned:

(1) As a rule, or in the greater number of cases at least, in the development of pathological conditions functional disturbances precede detectable structural changes in the fundus. An earlier diagnosis is thus rendered probable by the subjective method of examination. The hope of successful treatment rests upon an early diagnosis.

(2) A more minute search can be made by the subjective than by the objective methods of examination. It is obvious that the minuteness of examination by the subjective methods is limited only by the threshold of space discrimination.

(3) Pathological disturbances posterior to the fundus of a kind or of a magnitude that do not produce a visible change of structure in the fundus cannot be detected by the objective methods of examination. There is a possibility that many of these can be detected at an earlier stage in their development and all of them at some stage in their development by the subjective methods.

(4) Results by the subjective methods of examination can be subjected more or less satisfactorily to numerical treatment and comparison.

The importance and the need of the subjective methods of examination are coming to be widely understood and realized in medical circles. The work, however, is still in its infancy. Much of the knowledge that is needed for an intelligent procedure is not yet available. To the acquisition of this knowledge the present study is dedicated as a minor but fundamental contribution.

II. HISTORICAL SUMMARY

The discovery of the blind spot by Mariotte (3) in 1668 was to a large extent the incentive to the examination of the response of the peripheral retina. It was not until 1801, however, that Thomas Young (4) published the first account of an attempt to explore the retina with a view to determining the form and extent of its sensitive surface. In 1804 Troxler (5) discovered that the peripheral and central portions of the retina were not alike in their characteristics. Twenty years later Purkinje (6) confirmed this discovery. Also, he was the first to indicate a difference in the extent of the sensitivity to light and to color and a variability both in the extent of the zone in which the different colors could be seen and in the hue in which they were sensed in the different parts of the retina.

This discovery was followed by numerous attempts to determine the way in which the color response and the sensitivity to color varied from center to periphery. Results differed widely, however, with different investigators. This was due largely to the fact that the influence of many important variable factors was either unnoticed or neglected. It was evident from these results that until a consistent and systematic study should be made of the factors involved and an acceptable method of standardizing these factors and of estimating sensitivity should be found, no authoritative statement could be made of the extent of color sensitivity or the relation of the sensitivity at one point on the retina to that at any other point.

In 1910 Ferree and Rand (7) began a series of studies planned for the purpose of determining the effect of the factors which influence the response of the retina to color and of devising means of standardization and control. They also developed methods and apparatus whereby the amounts of stimulus used could be specified in comparable terms. The quantitative and qualitative effects of the variable factors which they found to influence the response of the retina to color have been adequately

dealt with by them in various publications. A brief review of the work to date will be given here, however, for the sake of continuity and the orientation of the present study in relation to the work already done.

Among the factors which have been found to influence the response of the retina to color the following may be mentioned; intensity, composition and purity, and size or visual angle of stimulus; brightness of preexposure and surrounding field; intensity of the general illumination and state of adaptation of the retina; and length of exposure. These are the more important factors which influence variability of result in any given individual. The factors which cause a variation of result from individual to individual will not be discussed in this study.[1]

A. Brightness of Preexposure and Surrounding Field

Previous to the investigations by Ferree and Rand, the effect of brightness of preexposure and surrounding field had been recognized only in a very general way and with little understanding of its influence. No quantitative estimate of the effect had been made, nor had there been any attempt at standardization that showed a comprehensive knowledge of the way in which the factor produced its effect.

Some attention had been given, however, to the effect of the brightness of the field surrounding the stimulus on the degree of eccentricity of the apparent limits of sensitivity to the different colors. In fact it was the recognition by Krükow (8) that former methods had allowed the retina to become unequally fatigued to chance objects in the surroundings that led to the substitution of the campimeter for the perimeter in investigations of the color sensitivity of the retina. The campimeter as an instrument for the investigation both of central and peripheral sensitivity is of value in that it provides a convenient means of changing the

[1] For a discussion of these factors, see Ferree, C. E., Rand, G., and Monroe, M. M., Studies in Perimetry, 3, Errors of refraction, age and sex in relation to the size of the form field, *Amer. J. Ophth.*, 1929, 12, 659–664; Errors of refraction, age and sex in relation to the size of the form field and preliminary data for a diagnostic scale. *Bulletin of the Johns Hopkins Hospital*, 1929, 45, 295–314.

brightness of the field surrounding the stimulus. That is, by means of the campimeter the brightness induction from the surrounding field may be eliminated, standardized, or varied at will to suit the needs of the investigation. Krükow, however, seems to have had little realization of the versatility of the instrument. No study was made of the effect of different backgrounds and he did not seem to know the principles underlying the effect of background. He used first a gray and later a black surrounding field.

Incomplete and somewhat rudimentary investigations of the effect of brightness of the surrounding field were made by Aubert, Woinow, Fernald, Hess and Tschermak. Woinow (9) found the color limits to be the same when either a dark or a light background was placed behind the stimulus and concluded, therefore, that the limits of color sensitivity were not influenced by the brightness of the surrounding field. Aubert (10) and Fernald (11), on the other hand, found a difference in the limits for pigment stimuli when placed on light and dark backgrounds, but disagreed as to the direction of the effect. Aubert obtained wider limits for red on black and for yellow, green and blue on white backgrounds, except for very small stimuli; Fernald obtained wider limits for all colors except red with dark than with light surroundings. Hess (12), and later Tschermak (13), observed pigment stimuli through an opening in a gray screen so arranged that it could be lightened or darkened by turning toward or away from the light. They both found that the limits of sensitivity to color were widest when the surrounding field was equal in brightness to the stimulus. If the stimulus appeared lighter or darker than the surrounding field, the limits were narrowed in proportion to the loss of saturation of the stimulus due to the influence of the background.

Rand (14) in 1913 made a study of the amount of white or black induced by surrounding fields of black or white at two points in the peripheral field. Stimuli subtending a visual angle of 3°26′ were used under two conditions of daylight illumination: 390 ft.-c. and 1.65 ft.-c., vertical component. Grays of the brightness of the four principal colors of the Hering series of pigments were used as stimuli and the screen of the rotary cam-

pimeter as inducing surface. The amount of induction was measured on a rotating disc placed immediately behind the fixation point in such a way that it was not subject to induction from the campimeter screen. This disc was composed of adjustable sectors of the gray used as stimulus and of white or black depending on the quality of the induction from the surrounding field. The sectors were adjusted until the sensation aroused by their fusion matched the stimulus in brightness as seen in the periphery at the point investigated. In general an increase in the amount of induction was found with increase of distance from the center of the field, with decrease of illumination, and with increase in the brightness difference between the two surfaces. Determinations were then made of the color thresholds at the same points in the peripheral field as were used in the measurement of amount of induction, and on the limits of color sensitivity in two meridional quadrants under the following conditions: (a) With a surrounding field of black, white or a gray of the brightness of the color. For these determinations the influence of the factor of preexposure was eliminated by making it of the same brightness as the stimulus. (b) With a preexposure of black, white or gray of the brightness of the color. For these determinations the influence of the factor of surrounding field was eliminated by making it of the same brightness as the stimulus. And (c) with both preexposure and surrounding field of black, white or gray of the brightness of the color. An explanation of the results obtained was offered in terms of the conditions of induction from the surrounding field and preexposure and of the inhibitive action of this induction on the chromatic component of the sensation.

In 1920 the investigation of these factors was continued by Ferree and Rand (15). The limits of sensitivity were determined in sixteen meridional quadrants by means of the rotary campimeter. Stimuli of red, yellow, green and blue Hering pigments were used subtending a visual angle of 3°26′ under a constant daylight illumination of 42 ft.-c. vertical component, 12.5 ft.-c. horizontal component. The limits were determined for surrounding fields of black, white and gray of the brightness of

the stimulus, the influence of the factor of preexposure being eliminated; for preexposures of black, white and gray of the brightness of the color, the influence of the factor of surrounding field being eliminated and for both surrounding field and preexposure of black, white and gray of the brightness of the stimulus. In this study and in the work by Rand in 1913, the effect of preexposure and surrounding field on the limits of color sensitivity was found to be influenced by the following factors: (a) the region of the retina in which the color response terminated for the conditions used: (b) the brightness difference between the color and its background in this region; (c) the illumination of the retina at this point; and (d) the inhibitive action of the achromatic on the chromatic aspect of the sensation in this part of the retina. In general it was found that the widest limits were obtained for all the colors when the surrounding field and preexposure were of the gray of the brightness of the stimulus. For red and yellow, the colors which darken most in passing into the peripheral field, wider limits were found with the black than with the white surrounding field and preexposure, particularly in the temporal half of the field; for green, wider limits were found with white than with black surrounding field and preexposure; and for blue the limits for the two conditions were interlacing.

In 1924 Ferree and Rand (16) published data on the effect of brightness of preexposure and surrounding field on the size and shape of the color fields for stimuli of different sizes. These determinations were made on the Ferree-Rand perimeter (17) with a constant illumination of 7 ft.-c. Again three brightness values were used as preexposure and surrounding field, a white, a black and a gray of the brightness of the color at or near the point at which the limits of sensitivity occur. The stimuli used were a red, green and blue of the Heidelberg series of pigment papers. The sizes employd subtended visual angles of 2°, 1°, 0.5° and 0.17° respectively. They obtained the widest angular limits of the color fields when the preexposure and surrounding field were of the same brightness as the color for all of the colors except blue with the very small 0.17° stimulus, in which case the

widest field was obtained with the black preexposure and surrounding field.[1] The comparative effect for black and white surrounding fields and preexposures was found to vary considerably with the size of stimulus used, both in amount and in some cases in direction. For red, wider limits were always obtained with a black than with a white preexposure and surrounding field. For green, wider limits were always obtained with a white than with a black preexposure and surrounding field. For blue, the limits interlaced with the 2° stimulus but with the 1°, 0.5°, and 0.17° stimuli wider limits were obtained with the black than with the white preexposure and surrounding field. In general, the amount of difference in effect between the two conditions increased with decrease in the size of stimulus. With the white preexposure and surrounding field the area of field for red with stimuli subtending visual angles of 2°, 1°, 0.5°, and 0.17° was reduced 16.9, 60.5, 85.4 and 84.2 per cent as compared with the area for preexposure and surrounding field of gray of the brightness of the color; for green this reduction was 7.5, 22, 34.3, and 61.5 per cent; and for blue, with stimuli subtending visual angles of 2°, 1°, and 0.5°, it was 9.1, 50.6, and 55.3 per cent respectively. With the black preexposure and surrounding field the reductions for red were 5.8, 13.5, 19.8 and 34.9 per cent; for green, 30.6, 51.2, 71.9 and 83.1 per cent; and for blue, 6.5, 11.4, and 13.5 per cent respectively. In the case of blue for the stimulus subtending a visual angle of 0.17° the field, as already stated, was widest for the black preexposure and surrounding field. The reduction produced by the gray preexposure and surrounding field was 29.6 per cent; by the white preexposure and surrounding field, 86.2 per cent.

[1] This result is quite exceptional. It seems to be obtained only when very small stimuli are used. Usually the widest fields are obtained with a preexposure and surrounding field of the brightness of the color. Blue, however, sustains a very close qualitative relation to the gray of the Hering series which matches it in brightness. When very small in size it seems to escape observation entirely on such a background after a certain eccentricity is reached. For this reason the small amount of induction from the black background seems to be a favorable rather than an unfavorable factor. That is, the influence of this induction on rendering the stimulus more different from its background seems more than to compensate for the small amount of inhibitive action on the chromatic component of the sensation.

In 1925 a study of the effect of the brightness of surrounding field on the limits of the blind spot to form and color was made by the writer, in collaboration with Ferree and Rand (**18**). All factors other than the ones under investigation were carefully controlled by means of the Ferree-Rand perimeter. The area of the blind spots obtained with a 0.25′ stimulus at 33 cm. were measured by means of a planimeter. A comparison of these areas showed the blind spot for achromatic stimuli to average 7.6 per cent larger on a white than on a black field, *i.e.*, a black stimulus on a white field gave a slightly larger blind spot than a white stimulus on a black field. This difference was in the direction to be expected. That is, the influence of the irradiation of the white excitation on the retina would tend to increase the area stimulated in case of the white stimulus on the black field and to decrease it in case of a black stimulus on a white field. Also the sensation difference between stimulus and background, an important factor in determining visibility, is greater in case of a white stimulus on a black ground than in case of a black stimulus on a white ground, due probably to a difference in the amount of physiological induction.[1] Although the blind spots for the chromatic stimuli were all much larger than for the achromatic stimuli, the least difference was found when the brightness of the surrounding field was the same as that of the color; the greatest, when the surrounding field was white. On the gray of the brightness of the color, the blind spots for chromatic stimuli were 40–45 per cent larger than those for the achromatic stimuli; on the black field they were 47–71 per cent larger; and on the white field, 72–132 per cent larger.

From the results of the above studies it is obvious that brightness of preexposure and of surrounding field are important variable factors influencing the response of the retina to color, and must be subjected to careful control if correct and reproducible results are to be obtained in investigations of sensitivity and response to color. The need for this control is particularly great in work on the peripheral retina.

[1] See C. E. Ferree, and G. Rand, Intensity of light and speed of vision studied with special reference to industrial situations, Part II, *Trans. Illum. Eng. Soc.*, 1928, **23**, 507–542.

B. Intensity of the General Illumination

The effect of the intensity of the general illumination of the retina on color response has been recognized since the time of Purkinje and Aubert, and a number of experimenters, among them Kramer, Wolffberg, Rand, and Ferree and Rand have studied it in varying degrees of detail. In the studies to be reviewed in this section, pigment stimuli were used and no separation was made of the two effects of intensity of illumination: (a) on the amount of light reflected from the pigment stimuli; and (b) on the state of general adaptation of the retina. Indeed prior to the work of Ferree and Rand no analysis had been made of the number of ways in which changes in general illumination affect color sensitivity and of the relative importance of each; nor had an adequate control of illumination been exercised. Even when attention was given to the factor, earlier experimenters had been content to take such rough precautions as working only on bright days at stated hours. Fernald (11) and Thompson and Gordon (19), for instance, attempted a rough control of illumination by lowering shades on bright days and raising them on dark days; and Kramer (20) specified only that the day was cloudy or sunny.[1]

Kramer determined the effect of different intensities of day-

[1] Indeed at this time instruments for measuring or even sensitive methods for detecting changes in the illumination of a room were not available. For use in their earlier work Ferree and Rand (*Psychol. Rev.*, 1912, **19**, 364–373: An optics-room and a method of standardizing its illumination) devised a method of reproducing the illumination of an optics-room based on the extreme sensitivity of the peripheral retina to brightness contrast and to the fact that very small changes in the illumination of the room produce a change in the amount of this contrast. Their method briefly consisted of measuring the amount of contrast induced by a white background on a light gray stimulus when viewed at a point 25° from the center of the field in the temporal quadrant under an intensity of illumination chosen as the standard. If this intensity was either increased or decreased by very small amounts, the measuring disc no longer matched the stimulus. The optics-room was provided with an elaborate series of curtains by means of which small or gross changes in the illumination could be produced until the intensity giving the standard amount of contrast was obtained. The method proved to be very sensitive and feasible. The principles involved have since been developed by them into a sensitive method of heterochromatic photometry. (A New Method of Heterochromatic Photometry, *J. Exper. Psychol.*, 1916, I, 1–12.)

light and various artificial illuminations by comparing the distances at which red, yellow, green and blue pigment stimuli on a black background could just be sensed. He found in every case that a decrease in intensity of illumination lessened the distance at which the colors could be perceived. He ignored the fact, however, that white was induced across the stimulus by contrast with the black background and that the amount of this induction varied with each intensity of illumination as well as with the different colors.

Wolffberg (21), who had at hand one of the essentials for standardizing, *viz.*, a method of making gradual changes in the illumination of his room, and who from his results could have derived the other essential, a method of identifying and designating the illumination used, showed that the response to pigment stimuli varied with the intensity of illumination but failed to draw attention to the importance of standardizing. His method of working was as follows. In a room illuminated by daylight, he changed the illumination by fastening from one to fifteen thicknesses of tissue paper over the window. The illumination with the window uncovered was designated as 15/15; covered with one thickness of paper, 14/15; etc. He then determined the size of a pigment stimulus necessary just to sense the color at a given distance (5 meters) for the different illuminations. In the peripheral field he determined the change effected in the limits by these fifteen illuminations. He found that a decrease in illumination affected the sensitivity to color more than to white in the central field and narrowed the color fields. The decrease in the breadth of field however, was not more than 15 degrees in any quadrant. The relative order of extent of field for the different colors was not affected. The order of size from greatest to least for all illuminations used was blue, red and green.

As has been indicated, Wolffberg could have utilized the conditions which he had at hand for standardizing any intensity of illumination which he wished to use, *i.e.*, for a given size of test-object the distance at which its color was just recognizable could have been determined for the illumination in question. This illumination could then have been reproduced at any subsequent

time by adding or subtracting layers of tissue paper until the test condition was satisfied.

Rand (22) in 1912 pointed out the wide variability in the eye's response, central and peripheral, to pigment stimuli when the work was done under uncontrolled daylight illumination. For the study of the effect of intensity of illumination, two intensities were chosen, a high illumination of 390 ft.-c., vertical component, and a low illumination of 1.65 ft.-c. The study was planned to investigate the effect of this amount of change of illumination on the limits of sensitivity to the stimuli used and on the value of the threshold at the fovea and at 15°, 25° and 30° from the fovea in the nasal horizontal quadrant of the field of vision, when surrounding fields were used of gray of the brightness of the stimulus at the point investigated, and of white and black. Measurements were also made of the amount of black and white induced by the white and black screens respectively on gray surfaces of the same brightness as the pigment stimuli under the conditions used. A decrease in the intensity of the general illumination was found to increase the amount of induction produced by the surrounding field. This effect was greater for the white than for the black screen. The decrease in illumination also caused an increase in the value of the threshold and a contraction of the color fields which varied in amount with the background used. These determinations showed that one of the important causes of change in the color response with variable illumination is due to the change in the brightness relation between stimulus and background with change of illumination. It was pointed out, therefore, that it was impossible to control or eliminate the factor: brightness of surrounding field, unless the intensity of the general illumination was held constant. This was found to be true also of the effect of preexposure.

The effect of change in the intensity of illumination of the arm of a perimeter on the size and shape of the color fields was determined by Ferree and Rand (23) in 1922. Five intensities of light were used, giving illuminations of 51, 17, 7, 3 and 0.3 ft.-c. These intensities were obtained without change in the color of the light by the insertion of neutral filters of appropriate density in

the aperture of the lamp-house provided for the illumination of the arm of the perimeter. In order to show how these illuminations compared with the daylight illumination falling on the perimeter arm in an ordinary room, measurements were made of the daylight at the level of the perimeter arm in a room with a window, southern exposure, the lower sill of which was somewhat higher than the level of the perimeter arm when placed in the horizontal position. It was found that the highest illumination, 51 ft.-c., was the same as that falling on the perimeter arm at the fixation point when facing the window at 1 p.m. on a bright winter day; the second highest illumination, 17 ft.-c., was the same as that falling at the fixation point at 2.30 p.m.; the third highest illumination, 7 ft.-c., the same as that falling on the fixation point at 3.45 p.m.; and the fourth, 3 ft.-c., the same as that falling on the fixation point at 4.15 p.m. The fields were taken with all the controls used in connection with the Ferree-Rand perimeter. In every case the surrounding field and preexposure were of the gray of the brightness of the color at the point investigated under the illumination used.

The decrease in illumination from 51 to 3 ft.-c., corresponding to that change in illumination which occurred in a well-lighted room between 1.00 and 4.15 p. m., narrowed the limits for red by amounts ranging in the different meridians from 11–37 degrees; for blue, from 13–37 degrees; and for green, from 10–19 degrees. The decrease from 51 to 0.03 ft.-c. narrowed the limits for red by amounts ranging in the different meridians from 27–72 degrees; for blue, from 29–61 degrees; and for green from 22–45 degrees. Changes in the shape and relative breadth of the color fields were also noted with changes in illumination. At 51, 17 and 7 ft.-c. for instance, the boundary of the blue field intersected that for red 6, 4 and 3 times respectively; at 3 ft.-c., it lay entirely within the boundary for red, while at .03 ft.-c. it lay almost entirely outside the boundary for red.

It is obvious from these results that control and standardization of the general illumination are necessary not only for problems of research but also from the standpoint of practical perimetry, if dependable results are to be obtained, either in diagnosis or in

checking up the advance or recession of a pathological condition. Although the above investigations are sufficient to show the need for a control and standardization of the factor of general illumination, they have shown its effect only through its influence on other variable factors. Its direct effect upon the sensitivity of the retina to color through changes in the state of adaptation of the eye has not been shown, except for central vision, prior to the present study.

C. Time of Exposure of Stimulus

That time of exposure is an influential factor in the determination of the chromatic response of the retina has long been recognized. As early as 1711 Bacon (24) observed that visual sensation does not rise to its maximum value immediately. This was noted also by Beudant (25), Plateau (26) and Swan (27). No experimental investigation of the time required to reach this maximum was made, however, before that of Exner (28) in 1868. In 1834 Plateau (26) also reported a change in the response to chromatic stimuli as a result of fatigue or adaptation to the stimulus, *i.e.*, as a result of exposure-time greater than that required to arouse the maximum sensation. Since that time frequent investigations of the time factor have been made. The only quantitative determinations, however, have been those made by Bills and by Ferree and Rand for the rise of sensation, and by Almack for chromatic adaptation.

Previous to these latter determinations, the rise of sensation had been investigated by Swan (27), Charpentier (29), Lough (30), Broca and Sulzer (31), Martius (32), Büchner (33), and Berliner (34), by direct methods; and Exner (28), Lamansky (35), Kunkel (36), Dürr (37), and MacDougall (38) by indirect methods of determination. No two of these methods were the same in all essential details:—experimental technique, intensity and composition of light used, etc. Moreover, the control and specification of conditions has not been such that a comparison of their work can be made from their publications. In only two cases was light of spectrum purity used and Dürr alone speci-

fied the wave-length. Broca and Sulzer attempted to equalize the lights in brightness. In no other case was any attempt at equalization of light intensities made, either photometrically or radiometrically. In some cases, the determinations were made in terms of the achromatic aspect alone; in some, in terms of the chromatic; in others both aspects were included in the determination; while in still others no distinction was made between the two aspects. In most cases, also, there was no attempt to determine more than the time required for the sensation to reach its maximum. The principal points of interest have been the comparison of the time required for the different colors to reach their maximum, a comparison of the optimum time for colored and colorless light, and a determination of the effect of intensity of light on this optimum time. Conflicting results have been obtained. Kunkel, Lamansky, Broca and Sulzer, and Martius found that the length of time required for sensation to reach its maximum varied with the color used, but they disagreed as to the values of this optimum time for the different colors and their ratios to each other. MacDougall, Dürr, and Berliner, on the other hand, concluded that the time required for sensation to reach a maximum was independent of the color of the sensation. They, too, disagreed, however, as to the value of the time required.

The four who worked with both white and colored lights agreed that there was a characteristic difference in the time required for the two kinds of light to produce their maximum effect in sensation, but disagreed as to the amount of that difference. Dürr, for example, found that colored light required approximately twice as long to produce its maximum effect as white light; MacDougall and Martius, that the time for colored light was within the range of values for white light and Broca and Sulzer, that the time was longer for blue and shorter for green and red than for white light. Broca and Sulzer alone specified the intensities of the lights used.

The time required to reach a maximum of sensation was found to vary, also, with intensity of light by all except Dürr, who stated that the time was independent of intensity.

With the hope of obtaining a more reliable set of results and of arriving at a better evaluation of those already obtained, Bills (39) in 1920 undertook the study anew. Several methods were used; the more promising of the older methods and three new methods devised by Ferree and Rand. In order that a comparison might be made of these methods, the same observer, the same state of adaptation of the eye, the same wave-lengths and intensity of light, and as nearly as possible the same apparatus were used. The stimuli were spectrum lights made equal photometrically and measured radiometrically.

In the method chosen as most feasible and convenient, and having the greatest sureness of principle, the intensity of light was held constant and such changes made in the exposure-time as would give just noticeable differences of brightness in the sensation aroused. The value of exposure-time, no further increase of which caused a noticeable increase in brightness, was accepted as the optimum and the sensations produced by the other exposures were rated in terms of the just noticeable differences from zero.

By this method a difference was found in the rate of rise of sensation for the different wave-lengths and for white light, *i.e.*, the retina is not only selective in the amount of its response to wave-length but it is selective also in the lag it shows in giving its full response. With the highest intensity used, 1.21 m.c., the rate of rise of sensation from fastest to slowest up to within two j.n.d.'s of the maximum for green was green, yellow, white, and red. No determination was made for blue. At the lowest intensity, 0.057 m.c., the order was yellow, red, blue, green, and white. With an intermediate intensity, 0.15 m.c., the order as to rate of rise varied at different stages in the development of the sensation. With increased intensity the time required to produce maximum response was decreased. This decrease was more rapid for green and blue and slower for red and yellow. The optimum time of exposure for sensation to reach a maximum at 0.057 m.c. was for red, yellow, green, blue and white respectively 0.164, 0.103, 0.190, 0.210 and 0.216 seconds. The work was done under conditions of dark adaptation and with a stimulus

subtending a visual angle of 0.43° in the horizontal and 1.63° in the vertical dimension.

This method was used also by Ferree and Rand (40) in a determination of the curves of rise of sensation for red, yellow, green and blue spectrum lights and the light from a carbon lamp, in connection with a study of the equality of brightness and flicker methods of photometry. The rise of sensation to the maximum was determined for the five lights at one intensity only, 12.5 m.c. At 25 and 50 m.c. the curve for the rise was determined only to the level given by an exposure of approximately 0.04 seconds, the value of the individual exposures for the rate of succession giving the highest sensitivity to flicker photometry. The work was done under conditions of light adaptation with an illumination equal in meter-candle value to that of the stimulus being used, and with a circular stimulus subtending a visual angle of 1.9°. At 12.5 m.c. the optimum time of exposure for red, yellow, green, blue and the carbon lamp were respectively 0.233, 0.195, 0.174, 0.157 and 0.254 seconds.

The results of their work in so far as they pertain to the rise of sensation may be summarized as follows: (1) Lights of different wave-lengths or composition rise to their maximum value in sensation at different rates, *i.e.*, they show different amounts of lag. (2) The lag changes with intensity of light and the change is different in amount for the different wave-lengths. (3) The order of ranking as to rate of rise for the different wave-lengths changes at different points from minimum to maximum, *i.e.*, the curves representing the rise interlace or crisscross. It is also inferred by them from the results of auxiliary experiments that the rate of rise, perhaps also the differential effect of wave-length and intensity on the rate of rise, are affected, in addition, by the size or visual angle of the stimulus, the state of adaptation of the eye, and the region of the retina stimulated.

Before the work done by Almack, the effect of exposures longer than those required for the sensation to reach its maximum had been studied in its relation to loss of saturation of the stimulus, to changes in hue, and also to changes in brightness. In the first group may be included the determinations of Plateau (41), Bokowa (42),

Aubert (43), Burch (44), Beck (45), Porter (46), Edridge-Green (47), Brückner (48), Sheppard (49), Troland (50) and Ssamujlow (51); in the second those of Exner (52), Hess (53), Voeste (54), and Sheppard (49); and in the third that of Schön (55). In general the problems had not been clearly formulated, and the experimental conditions were poorly controlled. As a result of their experiments, however, Aubert, Burch and Ssamujlow claimed that the length of adaptation required to produce partial or complete loss of saturation varied with the hue; Sheppard, that it varied with saturation; and Sheppard and Troland that it varied with brightness. Most colors were found to change in hue towards yellow or blue. A few colors, however, in certain regions of the spectrum, were reported stable in hue.

In Almack's (56) experiments, spectrum lights measured in radiometric units were used as stimuli and the sensitivity of the retina was rated in terms of the amount of energy required to arouse the threshold of sensation at the end of each period of fatigue or adaptation. The study was made for lights equalized in all ways, subjective and objective, in which amounts of colored light may be specified, *i.e.*, photometrically, radiometrically, and with reference to the saturation of the color sensation aroused. The experiments were conducted also under conditions of both light and dark adaptation.

She concludes that loss of sensitivity as a result of adaptation to a stimulus exposed for a longer time than that required to arouse the maximum sensation is an irregular function of four variables; wave-length, intensity, time of exposure, and general state of brightness adaptation of the retina; that saturation and brightness cannot properly be considered as factors in adaptation—rather, changes in hue, saturation and brightness are the conscious phenomena of chromatic adaptation; and that the rate of adaptation appears to sustain a direct relation to the state of sensitivity of the retina. That is, the rate is rapid at the beginning of the exposures, becoming progressively slower as the length of exposure is increased. Also the rate of adaptation for the dark-adapted eye which has a higher initial sensitivity, is much faster than for the less sensitive light-adapted eye; and the colors to

which the fresh eye is the most sensitive cause the most rapid loss of sensitivity.

It is evident from the foregoing results that time of exposure is a factor in the determination of the sensitivity of the retina to color that must be controlled and standardized if reliable results are to be obtained. Since the optimum time of exposure varies with the wave-length and intensity of the stimulus, and probably also with the size of stimulus, the state of adaptation, and the region of the retina stimulated, the best directions with reference to the control of the factor that can be given at the present time are to select a time which is certainly equal to or greater than the optimum for any of the conditions used in the experiment, keep it constant throughout the investigation, and specify the conditions used. Fortunately for the possibilities of an adequate control, the differential effect for wave-length and intensity of light, state of adaptation, etc., is slight for small variations when values greater than the optimum are used. That is, just what value shall be selected for a comparative rating of sensitivities, is of very great importance for values less than the optimum. For values greater than the optimum the point is of very much less importance. The optimum would of course be the desirable exposure time to use if that could be known for each experimental situation.

D. Size of Stimulus.

Of the various factors influencing color response, size of stimulus had been the most adequately treated by the early investigators. Its influence had been shown and the need pointed out for careful measurement of both the actual size of the stimulus and the apparent size, as determined by its distance from the eye of the observer. In fact, the first systematic investigation of the responses of the peripheral retina was made by Hueck in 1840 to determine the effect of this factor.

Investigations of the effect of area of stimulus on the limits of color sensitivity have been made by Hueck, Aubert, Woinow, Krükow, Raehlmann, Schön, Schirmer, Briesewitz, Tschermak, Kirschmann, Abney, and Ferree and Rand.

Pigment stimuli both colored and colorless were used by Hueck (57) and Aubert (58). Changes in effective size or visual angle were accomplished in two ways:—by varying the actual size and holding the distance constant and by varying the distance and holding the size constant. Both investigators found an increase in the size of the field of vision with an increase in the size of the stimulus.

Woinow (9), however, contradicted their assertion, claiming that this was not the case if the eccentricity of the point taken as the limit were measured from the inner edge rather than from the center of the stimulus. Krükow (8) confirmed Woinow's findings and stated that the boundaries of the color zones were absolute within certain limits of size of stimulus. Aubert (10) repeated his experiments and concluded as before that size of stimulus was a factor in determining the limits of sensitivity. He mentions the precaution as to measurement of the angular distance used by Woinow but does not definitely state that he himself used it. Raehlmann (59), Schön (60), Schirmer (61) and Briesewitz (62) all agreed with Aubert but failed to mention their method of measurement.

Tschermak (63) observed Woinow's precaution, yet obtained results agreeing with those of Aubert. The stimulus was placed behind the opening of a campimeter screen of gray paper, and its size regulated by means of gray slides which widened the opening either on the side within the visual field toward the fovea or on the other side, toward the periphery. Having determined the point in the periphery at which red and green appeared colorless, he widened the stimulus-opening first toward the fovea and then toward the periphery. Color was sensed in both cases.

In the first case no conclusion could be drawn since the inner margin of the stimulus was extended into the region of the retina sensitive to color. In the second case, however, the color was sensed when the area was increased without extending its margin into the field sensitive to color. Tschermak therefore concluded that the limits of color sensitivity are influenced by the area of the stimulus.

Kirschmann (64), in 1893, pointed out that different regions

of the retina react differently to an increase of area of the stimulus. In the upper and nasal regions he found that the fields sensitive to color were widened very slightly and never beyond certain limits by an increase in the area of the stimulus. In the lower and temporal regions on the other hand, he found the possibility of widening the fields to be great. Woinow and Krükow obtained their results in the nasal quadrant of the horizontal meridian. Tschermak does not state the region investigated. Should this have been the temporal region of the retina, his conclusions may be reconciled with those of Woinow in the light of Kirschmann's results.

Rand (14) pointed out that these variations in the effect of area in the different regions of the retina were in all probability due largely to differences in the rapidity with which sensitivity falls off from the center to the periphery of the retina in the several meridians; that when the decrease is gradual, as in the meridians having the widest limits of sensitivity, more effect may be expected than where the sensitivity decreases rapidly; also that another cause of variable results may have been the range of size of stimulus employed. Since the retina fatigues quickly to a very small stimulus, an increase in size up to a certain point would be advantageous. The margins of very large stimuli, however, may extend so far into the zone of insensitivity that a further increase is ineffective.

Abney (65), in determining at what intensity different spectrum lights were brought below the threshold of sensation found that size as well as intensity of stimulus is a determining factor in the result. A stimulus 2 inches in diameter, for example, was seen at a lesser intensity than a stimulus ½ inch in diameter. Furthermore, he found that it was not the area, but the shorter dimension of the stimulus, vertical or horizontal, which determined the intensity required to render the stimulus subliminal. The experiments when extended to the peripheral retina resulted in the same conclusions.

The most recent study of the effect of size of stimulus on the size and shape of color fields is that published by Ferree and Rand (66) in 1927. The fields were determined on the Ferree-

Rand perimeter with standard pigment stimuli under fixed conditions of illumination, background, and preexposure of the eye. Five sizes of stimulus were used subtending a visual angle of 0.17°, 0.5°, 1°, 2° and 5° respectively. Three brightnesses of preexposure and surrounding field were used, a white, a black, and a gray the brightness of the color at or near the limits of sensitivity. Size of stimulus was found to be second in importance only to intensity in determining the limits of the field. In the case of red and blue the 5° stimulus extended the limits of the color fields almost to that of the form field; that is, with a stimulus subtending a visual angle of 5° illuminated by 7 ft.-c. of light, the fields for red were only 6, and for blue only 11 per cent smaller than for a 1° stimulus of white on black. In the case of green, however, the optimum size of field obtained with a 5° stimulus was but 46 per cent of the form field. Change of size of stimulus produced the least effect with a preexposure and surrounding field of the brightness of the color.

It is evident from these results that care must be taken to measure accurately the size of the stimulus used in peripheral investigations, as well as its distance from the observer, preferably the angle subtended at the eye, and to keep these measurements uniform throughout the investigation. There has as yet been no standardization of the size of stimulus; that is, each experimenter who has recognized it as a factor has chosen what he considered to be the most favorable area and has used that area in all of his comparative determinations. There has been a recent tendency, however, to establish as standard that size of stimulus subtending a visual angle of 1°, a size which has been used by the writer in the present study.

E. Purity of Stimulus.

In all determinations of retinal sensitivity to color the purity of the stimulus must be taken into account. The presence of alien visible wave-lengths affects the results of a determination of chromatic sensitivity in two ways: (a) through physiological inhibitions and interactions it decreases the amount of the color

response, and (b) it increases the energy measurement. The influence of this factor is self-evident and requires no special investigation.

F. Brightness of Stimulus.

The brightness or white value of a color as a factor in the determination of the limits of sensitivity to color has been much confused with intensity in the literature on the subject. It may be well to consider this factor, therefore, before taking up the question of intensity. The confusion is attributable, somewhat, to a misinterpretation of terms, but chiefly to an inability to isolate the subjective factor brightness from the physical factor, intensity. As a result, the effect obtained by the variation of both factors has often been attributed to changes in brightness alone.

Bull (67) and Hegg (68) equalized pigment colors in brightness for the investigation of the peripheral limits of color sensitivity. They claimed Aubert as authority for so doing and made no tests of their own to determine the influence of the brightness of a stimulus on sensitivity. Aubert (69), it may be noted, had merely expressed a belief that in making fine determinations of sensitivity in the central field by decreasing the size of the stimulus until the threshold to color was reached, an equalization of brightness should be made. He confessed, however, that he was unable to demonstrate whether or not the brightness of a color affected the retina's sensitivity to that color, because he was unable to isolate the factors involved. Bull and Hegg, therefore, equalized their stimuli in making determinations of the limits of the color field apparently without knowing or investigating the need for making the equalization. Baird (70) also equalized his stimuli in white value, claiming not only Aubert as authority, but also Landolt, Abney, Raehlmann, Chodin, Klug, Bull, Hess and Hegg. The authority derived from Aubert, Bull and Hegg is obviously without foundation; that derived from the others, with the exception of Hess whose test was incomplete and wrongly devised, has been shown by Rand (14) to be fallacious and due to misinterpretation and confusion of terms. These points

have been so fully dealt with by her that further details will not be given here.

Hess (71), as we have stated, attempted to determine whether a light or dark color of equal intensity had the same or different limits of sensitivity. His test was simple and applied to but one color. It consisted of a comparison of the limit of sensitivity in the nasal quadrant to each of two pigment stimuli, made up respectively of 180° of green plus an equal amount of white, and of 180° of green plus an equal amount of black. In each case a background of the brightness of the darker color was used. He found the limits for the dark green to be 25°, and for the light green 13°.

His method is open to several criticisms. In the first place, he made no determination of the brightness difference between the colors of any set of standard pigments. His variation of the brightness component might therefore be either less or more than any difference that is apt to be found in the use of pigment colors. If less, his test is not sufficiently rigorous; if more, its results exaggerate. For instance, brightness mixed with color inhibits color sensation. This inhibitive action increases as the brightness mixed with color approaches white, and decreases as it approaches black. If the difference in brightness between the green mixed with white and with black respectively is greater than the brightness variation between the standard colors, a greater difference in the inhibitive action upon the color of the two stimuli, and therefore upon the intensities of the sensations aroused by them, is obtained than would occur as the result of the actual difference in brightness. Later investigations have shown that his variations were greater than any difference that is apt to be found in standard pigments. His results, therefore, do not give evidence that the brightness difference between standard pigments is sufficient to affect the limits of color sensitivity.

In the second place, he did not exercise a correct control of the brightness of the surrounding field and preexposure. By using a screen and preexposure of the brightness of the darker stimulus, he added a considerable amount of white to the lighter stimulus by contrast from the dark background and by after-image from

the dark preexposure, over and above the white added by objective mixing. Therefore, while his aim was to add equal amounts of white and black to his stimuli, he actually added a greater amount of white than of black.

Rand (14) made a determination of the brightness difference actually existing between the standard pigment colors at the periphery, and of the limits of sensitivity to stimuli lightened and darkened by these amounts; she also determined the maximal amount of black or white which could be added to equal amounts of color without changing the limits. She found that the amount of brightness variation which could be made without changing the limits of sensitivity to the color was considerably greater than the brightness difference existing between the colors.

No advantage is therefore gained by equating the standard pigment colors in white-value for a determination of the limits of sensitivity. On the contrary serious disadvantages are suffered. The following reasons were cited in support of this latter statement: (a) The hue of certain colors is changed when their brightness is altered, a difficulty encountered by both Chodin and Hegg. (b) Colored stimuli when equalized in brightness are necessarily reduced in saturation. And (c) the technique involved is extremely cumbersome.

It seems obvious, then, that this factor so troublesome to previous investigators may be safely disregarded in the determination of the limits of sensitivity to color with pigment stimuli.

The continued insistence as to its importance, however, has led to this rather full exposition of the fallacies involved. In determinations with spectrum light, equalization in brightness is impossible if the important criterion of purity of stimulus is to be maintained. In connection with spectrum stimuli, the question can therefore scarcely be raised. For some time to come, however, clinical work in perimetry must be done with pigment stimuli. It is towards the work in clinical perimetry, therefore, that this discussion is directed.

Finally it may be said that colors equalized both in brightness and saturation such as have more recently been recommended by Engelking and Eckstein (72) and prepared under their direction,

and which are presumably similar in their optical aspects to those used by Bull, Hess, Hegg and Baird, are so changed in hue, saturation and brightness as scarcely to be recognizable. One can hardly conceive that such colors would ever be very widely approved either for laboratory or clinic use.

G. Intensity of Stimulus.

Intensity is the most important factor conditioning the amount of response and the extent of the retina sensitive to a given color. Beginning with the observations of Purkinje (73) a dependence of color sensation upon the intensity of the stimulus has been recognized. Purkinje noted also that a colored stimulus gave a less saturated sensation in the peripheral than in the central retina. Since that time other earlier investigators have found (1) that with stimuli of minimal intensity the sensation of color is not aroused; (2) that the eye is not equally sensitive to the different colors; (3) that as the stimulus is moved from fovea to periphery progressively greater intensity is required to arouse sensation; and (4) that the extent of the color fields is determined within certain limits by the intensity of the stimulus.

In evaluating the results of studies dealing with this factor a discussion of the methods used to specify or equalize the intensity of the stimuli used cannot be avoided. These methods fall into three groups: (1) Specification of the intensity used in terms of some form of ratio of the initial intensity of the source of light used. Examples of this type of specification are values in degrees of the sectors used in work with rotating discs of pigment papers; width of collimator slit; setting of a Nicol prism; coefficient of transmission of filters; etc. From this type of specification comparisons can be made for responses under various conditions and in various portions of the field to a given composition and intensity of stimulus, but no comparisons are valid for stimuli of different compositions and intensities.

(2) Specification or equalization of the stimuli in subjective terms. The outstanding example of this type of specification and one that has had a great deal of influence on the formulation of color theory has been the attempt by Bull, Hess, Hegg and Baird

to equalize in subjective terms the stimuli used in a comparison of the limits of color sensitivity. Their equalizations were made in terms of brightness and of another subjective aspect arbitrarily selected, *i.e.*, the proportion in which the pairs of antagonistic colors must be combined to produce gray, or in terms of the Hering theory, to cancel each other. The first of these equalizations has been treated in the section: Brightness of Stimulus. The second is obviously not justified in any investigation of the comparative sensitivity of any part of the retina to the different colors. In the first place it is clear that the stimuli used in any investigation, the purpose of which is a comparison of sensitivity, should not be equalized in terms of any aspect of the function investigated. That is, if the selective reaction or sensitivity of the retina to different wave-lengths is the point under investigation, these same wave-lengths should hardly be first made equal in their power to arouse any reaction of the retina. In the second place, if the determination of the limits is to be considered any part of the problem of the rating of comparative sensitivities, the intensity of the stimuli should be specified in physical terms. Then the sensitivities at these limiting points can be represented inversely as the intensity of the stimuli. If there is to be any equalization, it is obvious that it should be in physical terms. The limits then presumably represent points of equal sensitivity. The limits obtained with stimuli equalized in cancelling power can have no possible value as data to be used for the rating of comparative sensitivities. In the third place, the bearing on color theory of the results obtained by an equalization in cancelling power is difficult to understand. It seems to have been supposed in terms of the Hering theory that stimuli so equalized should give coincident limits. To show that stimuli equalized in cancelling power are not equalized in power to arouse sensation does not require very long or very difficult experimentation.[1]

(3) Specification in c.g.s. units. By this method alone can a specification in absolute terms be given of the intensity of stimuli

[1] For a more detailed discussion of this method of equalizing intensities, see G. Rand: The factors that influence the sensitivity of the retina to color, *Psychol. Monog.*, 1913, 15, (1), No. 62.

of different wave-lengths, and only with stimuli so specified can a fair test be made of the comparative responses and sensitivity of the eye to different colors.[1]

With reference to the above methods of specification of intensity, it is obvious that the third is the only one that can be given serious consideration. It is equally obvious that in determinations of sensitivity, intensity can be considered a factor only in connection with the limits of sensitivity. Its historical place as a factor in the determination of the threshold and just noticeable difference of sensation is due to the use of the first and second of the above methods of specification. In the first method, for example, the threshold or just noticeable difference was taken as some fraction of a given stimulus. The value of this fraction, therefore, depended upon the intensity of that stimulus. It is scarcely needful to point out that with a proper procedure and specification the intensity of the stimulus is the measure of the threshold and just noticeable difference, not a factor in their determination.

The effect of intensity upon the limits of color sensitivity.

Three positions have been held with regard to the limits of color sensitivity: (a) that with sufficient intensity the color fields extend to the extreme periphery, coinciding in extent with the field for white light or form; (b) that the color fields do not extend to the extreme periphery, the limits for complementary colors being coextensive in the order from wider to narrower of blue and yellow and red and green; and (c) that the order of ranking as to breadth of field is blue, red, green.

The first of these views was held by Landolt (74) who stated that with sufficiently high intensity, spectrum stimuli, also pigment stimuli illuminated by a beam of sunlight in an otherwise dark room, could be recognized to an eccentricity of 90° in the temporal quadrant of the field. Landolt's results have since been

[1] For a discussion of the need of this method of specifying intensity of stimulus for work in psychological and physiological optics see Ferree and Rand, Note on the determination of the retina's sensitivity to colored lights in terms of radiometric units, *Amer. J. Psychol.*, 1912, 23, 328–332; A note on the needs and uses of energy measurements for work in psychological optics, *J. Philos., Psychol. and Sci. Methods,* 1917, 15, 457–462.

confirmed and extended by Ferree and Rand (75). Working in sixteen meridional quadrants with spectrum stimuli, they have shown that with sufficient intensities of stimulus the fields for color are coextensive with the form field.

The second view was held by Bull (67), Hess (71), Hegg (68) and Baird (70), all of whom claimed that when the investigation is made with stimuli equalized in brightness and in cancelling power, the limits for red coincide with the limits for green, and the limits for blue with those for yellow, the limits for blue and yellow falling farther out from the fovea than those for red and green.

Kirschmann (76), however, failed to find the coincidence of limits claimed by Bull, Hess, Hegg and Baird. Kirschmann made no attempt to equate his stimuli either subjectively or physically. The fact that his colors were not equated in intensity, however, does not explain the deviations he found in the limits, since the difference in the relative ranking of the complementary colors as to limits in the different meridional quadrants was such that a crisscrossing occurred. This is obviously not due to a failure to equate in intensity, for if the limits for colors equal in intensity fall at the same distance from the fovea, an inequality in intensity would cause a separation of the limits, but not a change in their relative position from quadrant to quadrant. Crisscrossing or interlacing can be explained only as the result of a peculiarity in the distribution of sensitivity.

The fallacy of the method of Bull, Hess and Baird has been pointed out. Aside from this, however, a close examination of their tables of results reveals no closer coincidence of limits than was obtained by Kirschmann. In the results of every observer it is found that in some quadrants there is coincidence of limits; in others the green field is wider than the red by 1°, 2°, or 3°; in still others it is narrower by the same amounts. The same is found to be true for blue and yellow. Such a variation was apparently felt to be insignificant, probably no greater than their normal mean variation for the rough conditions under which they worked. Rand (14) has pointed out, however, that a difference of 2° or 3° in limits is not insignificant when conclusions are to

be drawn from the results with regard to the relative sensitivity of the peripheral retina. Because of the abrupt falling off in sensitivity just before the limit is reached, found by Ferree and Rand, and to be discussed later, a difference of 2° or 3° in limits represents quite a large difference in sensitivity, *i.e.*, a difference in sensitivity sufficent to raise the threshold for the different colors in some cases as much as 50 per cent, in others over 100 per cent.

The third view that the ranking as to breadth was fixed in the order of blue, red, green, has been held in clinical perimetry. Any deviation from this order or any interlacing of the fields was believed to be symptomatic of pathology. That this ranking is an artifact due to the selection of intensity of stimulus used will be demonstrated in the experimental section of the paper.

In the first investigation made by Ferree and Rand (75) of the effect of intensity on the limits of color sensitivity, spectrum light was used, the intensity of which was specified in watts (10^7 ergs per sec.), and precautions were taken to control the other variable factors. Four intensities of spectrum light were employed: the prismatic spectrum of a Nernst filament operated by 0.6 ampere of current, intensity A; the colors of this spectrum reduced to 1/32 of their original intensity, intensity 1/32 A; an equal energy spectrum in which the colors used were all made equal in physical intensity to the blue (the color of least energy of the series called intensity A), intensity B; the colors of this series reduced to 1/32 of their original intensity, intensity 1/32 B. In addition a determination was made of the limits of sensitivity for the Hering pigments, red, yellow, green and blue, when illuminated by 130 foot-candles of daylight, and for the Heidelberg pigments, red, green and blue, under 51, 17, 7, 3 and 0.3 foot-candles.

For the spectral stimuli, narrow bands in the region of 670mμ; 581mμ; 522mμ and 468mμ were used. In every case the light was examined for impurities at the analyzing slit by means of a small Hilger direct vision spectroscope provided with an illuminated scale. When found, impurities were absorbed by thin gelatine filters, selected so as to cut out as little of the desired light as

possible. Other precautions exercised to control the influence of variable factors were as follows: (1) The determinations were made with the preexposure and surrounding field of the same brightness as the stimulus color at the limits of sensitivity. (2) The intensity of the general illumination was held constant at 30.5 ft.-c. horizontal component, for the spectrum colors and 130 ft.-c. for the pigment papers. This was accomplished by the use of an optics-room designed especially for the control and uniform distribution and diffusion of daylight illumination. (3) The amount of light entering the eye was made independent of variations in the size of the pupil. This control was easily obtained with the method of presenting the light to the eye used in the apparatus employed. That is, the light from the spectroscope was first collimated and then focussed on the eye, forming an image of the analyzing slit in the pupil and causing the stimulus-opening in the campimeter screen to appear uniformly filled with light. All that was needed therefore to maintain the amount of light entering the eye at a constant value was to keep this image always of the same size and smaller than the pupil. The stimulus-opening of the campimeter screen formed a visual angle of 3°26′ at the eye. (4) The correctness and constancy of the position of the head was secured by biting a mouth-board, the position of which for the exact location of the eye at the center of the system had previously been determined by a convenient appendage to the apparatus described in the article referred to.

At intensities A and B the limits of red, yellow and blue were found to coincide with the limits of white light vision. Green could not be made to have so wide an extent. At intensity 1/32 A, the fields in the order from widest to narrowest were red, yellow, blue and green. At intensity 1/32 B, in which the four colors had been made equal in intensity to the blue of the spectrum, 1/32 A, the limits for red, yellow and blue interlaced or criss-crossed. That is, at intensity 1/32 A with the distribution of energies found in the prismatic spectrum of the Nernst filament, the limits were concentric with both red and yellow outside the blue; but at intensity 1/32 B, when the four colors were made

equal to the blue of 1/32 A, interlacing and not concentric limits were obtained.

The Hering pigment stimuli under the intensity of illumination used, 130 ft.-c., horizontal component, also gave interlacing limits for red, yellow, and blue, with fields roughly comparable in breadth with those given by the spectrum of colors at intensity 1/32 B. With red, green and blue Heidelberg pigments under 51, 17 and 7 ft.-c. of light, as has already been discussed in the section on general illumination as a factor, interlacing limits for red and blue were again obtained, although the limits for blue tended progressively to pass within those for red as the illumination was decreased; at 3 ft.-c. the limits were concentric for all but one point, where they were coincident, with the red field wider than the blue; and at 0.03 ft.-c. they had reversed for the greater part of the field, the limits for blue lying outside the limits for red.

Results obtained then under carefully controlled conditions and objective measurement of the intensities of stimulus used, indicate that the extreme periphery of the retina is sensitive to color when sufficiently intense stimuli are employed and that for equal intensities, the only condition for which the true effect of distribution of sensitivities on the apparent limits can be ascertained, there is neither coincidence of limits for the colors red and green, blue and yellow, nor a concentricity of limits for the pairs of colors, nor is the order of ranking from widest to narrowest blue, red and green, as is claimed by the clinicians. For the greater part of the retina, with equal intensities of stimuli, the apparent limits for at least red, yellow and blue are characterized by a greater or less amount of interlacing.

Since the effect of such factors as intensity on the shape and size of the color fields and their order of ranking as to breadth can be understood only when a thorough knowledge is had of the actual distribution of sensitivities from point to point from center to periphery of the retina, and since a detailed investigation of the sensitivity gradient for the four colors red, green, blue and yellow from center to periphery of the retina has an important bearing on certain points of color theory, Ferree and Rand felt that a quantitative determination of the chromatic sensitivity of

the central and peripheral retina should be made. The determination of the limits gives very little knowledge of the sensitivity of the retina as a whole and its changes from point to point.

Prior to their work, very little investigation had been made of the sensitivity of the peripheral retina. Chodin (77), employing the Masson disc, had found that the size of sector needed to arouse the threshold sensation at the center was in order of smallest to greatest orange, yellow, green and blue; in the periphery, however, it was smaller for blue and yellow than for red and green. Raehlmann (78), using the Bunsen spectroscopic apparatus which provides for changes in the intensity of the stimulus by means of a Nicol prism, determined the thresholds for the different spectrum colors at the center and at 30° and 60° in the temporal quadrant of the horizontal meridian. He found the center of the retina most sensitive in order to green, yellow, blue, violet and red; the periphery, to yellow, blue, green, violet and red. Butz (79), using a similar apparatus, determined first the threshold value for each color at the center. Starting with this value as a unit, he then determined how much it had to be altered to give liminal sensations at 30° and at 60° in the horizontal temporal quadrant. He found (a) that the sensitivity increased from 0° to 30° and decreased from 30° to 60°; (b) that the amount of increase in sensitivity from 0° to 30°, and the amount of decrease from 30° to 60° were different for the different colors, *i.e.,* the ratio of liminal sensitivity to any two colors was not the same from center to periphery; and (c) that the amount of increase was greatest and decrease less in order for violet, yellow, blue, green and red. It would seem from the results obtained that the achromatic rather than the chromatic thresholds were determined by Butz.

In none of these investigations had any specification of stimuli with regard to intensity been made. The only conclusion which can be drawn from the results obtained is that the comparative sensitivity to the different colors is not the same at the center and the periphery of the retina.

In the investigation planned by Ferree and Rand a determination was to be made of the achromatic and chromatic sensitivities

to wave-length that would be as quantitative as is possible in work of this type; that is, spectrum lights of definite composition and purity were to be used as stimuli and the intensity was to be measured in terms of energy. The determinations were to be made at near-lying points from center to periphery of the retina in several meridians.

Such a study was begun and determination made of the thresholds of chromatic sensation in the nasal and temporal quadrants of the horizontal meridian (1). The work was interrupted at this point, however, by the pressure of other investigations, and the survey was not completed in the number of meridians planned. The stimuli used were narrow spectral bands in the regions of red (670 mμ), yellow (581 mμ), green (522 mμ) and blue (468 mμ). The method of obtaining the stimuli and the control of variable factors affecting the results were the same as those used in the investigation of the effect of intensity upon the limits of retinal sensitivity.

From their summary of results the following points may be cited: (1) The range of variation of sensitivity from the center to the periphery of the retina is great. For example, in the temporal quadrant the sensitivity to red was 900 times greater at the center than at the periphery, and for yellow, blue and green it was respectively 1650, 3280 and 3380 times as great. (2) The sensitivity decreased very irregularly and at a different rate in the different meridional quadrants. From this result, changes in shape would be expected to accompany changes in size of field. (3) The ratio of sensitivity to the different colors in the same meridional quadrant varied greatly from center to periphery. At some points, for example, the sensitivity to red was greater than to blue; at others the reverse of this was true. As the result of such shifts in relative sensitivity, reversals in order of ranking as to breadth of color fields should be expected with large changes in the intensity of stimulus or of any factor that causes extensive changes in size of field. (4) A red stimulus even of spectrum purity has the power of arousing the sensations both of red and yellow, red strongly and yellow weakly. At or near the point of reversal of the ratios of sensitivity to red and yellow comes the

change in hue from red to yellowish red. At this point the subthreshold yellow becomes supra-threshold. The same is true for the green stimulus. These changes in hue are the normal changes for spectrum red and green in passing from the center to the periphery of the retina when there is no achromatic effect of preexposure and surrounding field, that is, when preexposure and surrounding field are of a gray of the brightness of the color, and when the illumination of the room is constant.

Prior to the present study, there has been, so far as the writer knows, no other investigation of the color sensitivity of the peripheral retina in which there has been a control of variable factors and a quantitative treatment of the stimuli. From this study the pattern for the present study has been derived.

III. EXPERIMENTAL

The purpose of the present investigation has been a quantitative determination of the achromatic and chromatic thresholds of red, yellow, green and blue spectrum lights at near-lying points from the center to the periphery of the retina in as many meridional quadrants as possible.

The nearness to each other of the points investigated was determined by the rapidity with which the sensitivity decreased in the quadrants in question. In regions where the decrease was gradual the determinations were made at points separated by as much as 5° to 10°. In those regions, however, where the rate of change was rapid or other unusual features were present, the determinations were made at points separated by one or two degrees.

The determinations were made under both dark and light adaptation. For the work under light adaptation a general illumination of 7 ft.-c. was used. In the selection of this intensity of illumination we were governed by the fact that 7 ft.-c. is the illumination of the arm of the Ferree-Rand perimeter which has been adopted as the standard instrument for office and clinical practice by the American Ophthalmological Society. The intention was to make the present survey of the chromatic sensitivity of the retina under conditions that would render the results as nearly as possible applicable to the practice of perimetry. The determinations were made in the eight principal meridional quadrants of the field—horizontal, vertical, and oblique. Determinations could be made only for the chromatic thresholds for this condition of adaptation. Under dark adaptation, however, both the achromatic and chromatic thresholds were determined, also the photochromatic interval. In this case it was deemed sufficient to make the determinations in only four quadrants—upper and lower vertical and temporal and nasal horizontal.

The stimuli used were narrow spectrum bands in the red, 672.5mμ; in the yellow, 581.5mμ; in the green, 522mμ; and in the

blue, 468mμ. The intensity of the stimulus lights was measured and the amount of light entering the eye for each determination specified in energy units.

Because of the range of work covered it was found possible to use only one observer. The normality of the observer was carefully tested as to acuity, light and color sensitivity, and visual fields. Moreover, the eye used in the investigation was refracted

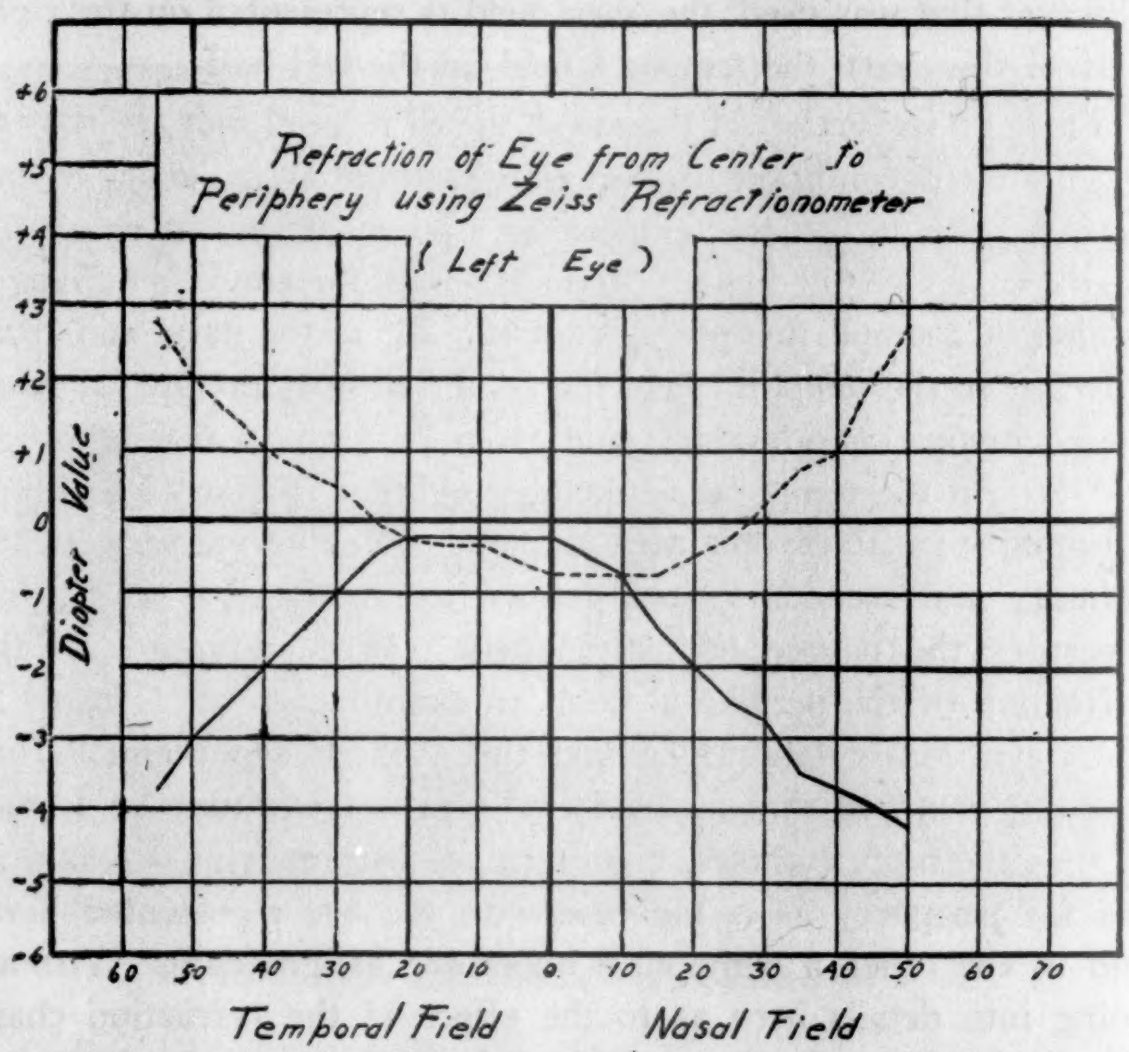


FIGURE 1. Showing refraction of the eye from center to periphery of the field in the 180° meridian.

from center to periphery in the nasal and temporal quadrants by means of a Zeiss refractionometer modified to serve the purpose.[1]

The condition of refraction of the peripheral field is shown in Fig. 1. In this graph the error of refraction at the different points is represented by the diopters of correction that would be

[1] For this refraction the writer is indebted to Dr. Gertrude Rand.

needed to produce emmetropia. The point in the field at which the examination was made is represented on the horizontal coordinate and the correction in diopters required to produce emmetropia on the vertical coordinate. No correction, or the condition of emmetropia, is designated by the horizontal zero line through the center of the graph. Above this are plotted diopters of hyperopia and below it diopters of myopia. Since it was the left eye of the observer that was used, the nasal field is represented on the right half of the chart, the temporal field on the left half.

From an inspection of the graph it will be seen that for the eye in question a condition of compound myopic astigmatism occurs from a point 20° on the temporal to a point 10° on the nasal side of the center of the field. At these points the condition changes to that of a simple myopia. From 10°-28° in the nasal and from 20°-25° in the temporal field the condition is again that of compound myopic astigmatism; and from 28°-50° in the nasal and 25°-56° in the temporal field, the condition is that of a mixed astigmatism with myopia predominant. The interval between the primary and secondary foci, known as the interval of Sturm, measures the degree of astigmatism. With reference to the refraction of the peripheral field, an examination of 21 cases in the Bryn Mawr laboratory and the Wilmer Ophthalmological Institute[1] showed that at least two types of eye may be found. In one, the more common type, a mixed astigmatism is found in the far periphery as is the case with the eye represented here, and in the other a compound hyperopic astigmatism. Without going into details here as to the effect of the refraction characteristics of the peripheral field on determinations of sensitivity, it will be sufficient to say that the eye used in these experiments belongs to what is probably the more common type.

For an investigation of the kind made in this study, the following provisions were needed:

1. An apparatus for presenting to the eye spectrum lights of high intensity and free from impurities throughout the range of wave-lengths selected.

[1] This study will be soon published by C. E. Ferree, G. Rand and C. Hardy.

2. Devices for reducing the intensity of the spectrum light continuously and by known amounts to very low values.

3. An apparatus for measuring the energy of the stimuli employed.

4. Provisions for a precise control and reproduction of the intensity of illumination of the campimeter screen.

5. Provisions for the control of fixation.

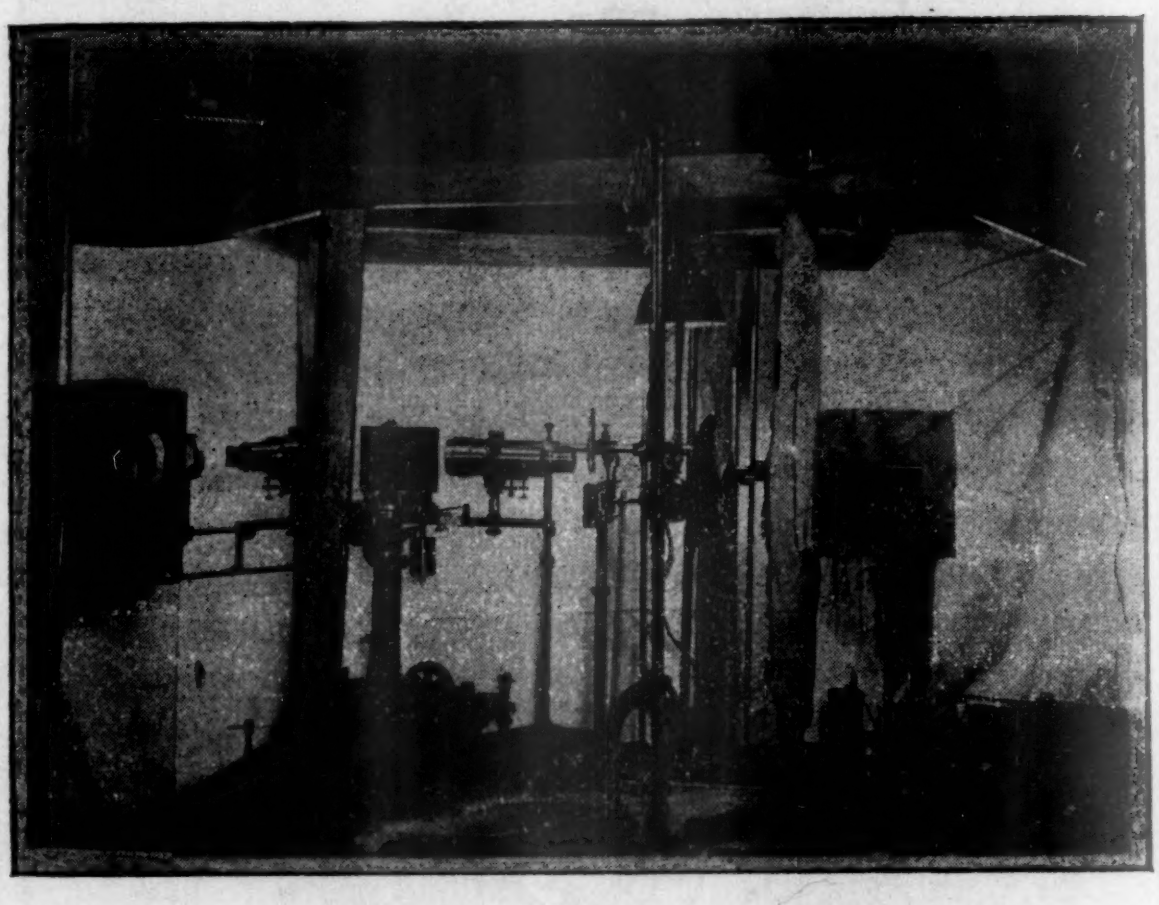


FIGURE 2. Showing the apparatus assembled for work.

6. Provisions for making the determinations under light and dark adaptation.

A photograph of the apparatus is given in Fig. 2; the arrangement of the apparatus and the path of the beam of light from the source to the eye are shown in Fig. 3.

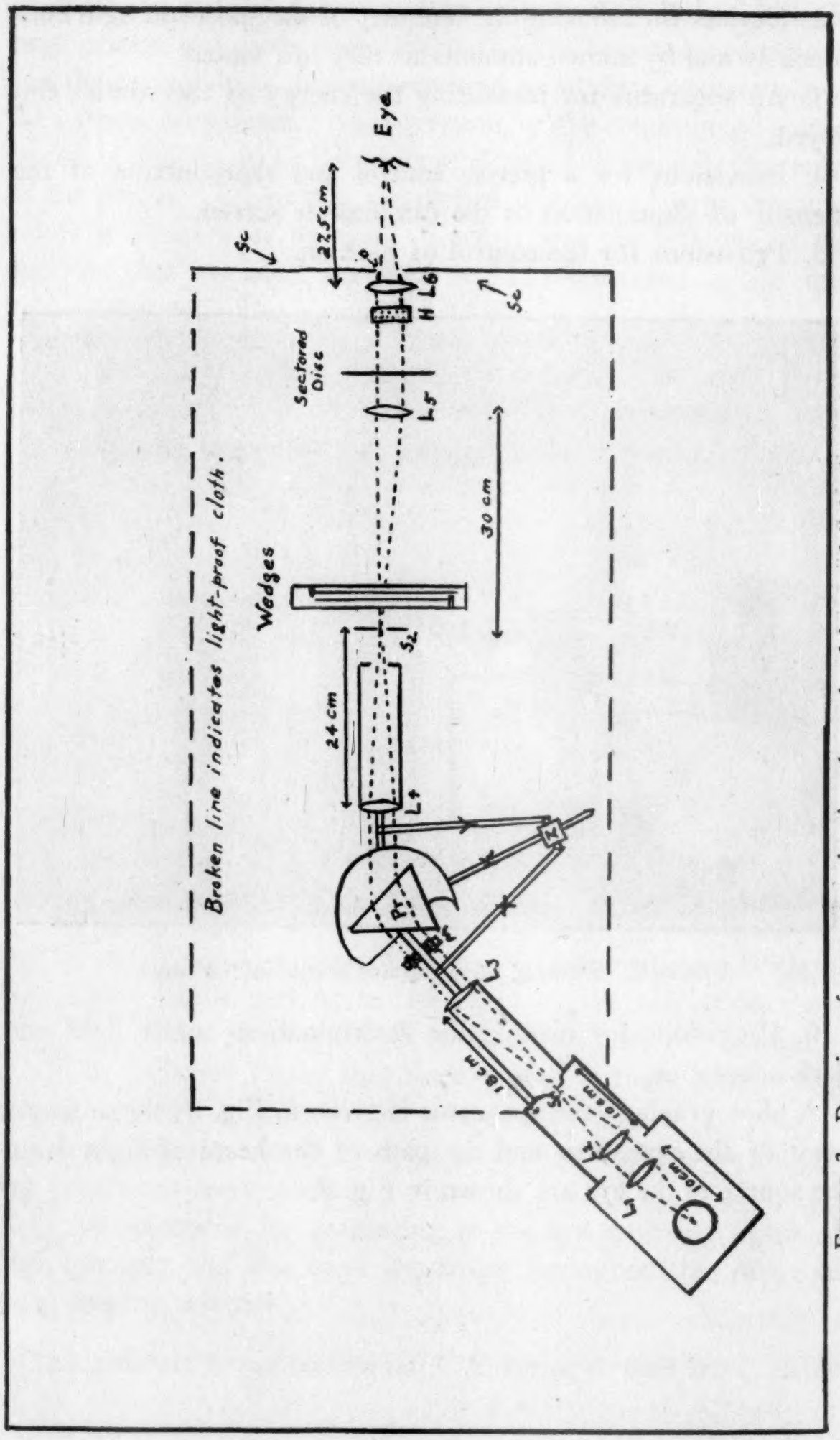


FIGURE 3. Drawing of apparatus showing the path of beam of light from the source to the eye.

A. Apparatus.

1. *The Source of Light.*

A tungsten lamp provided with a ribbon filament, made by the Nela Research Laboratories, was used as the source of light. The following reasons may be assigned for the use of this lamp: The Nernst filament used in much of the previous work can no longer be obtained. Moreover, the tungsten ribbon filament lamp gives a higher intensity of light and is less troublesome to use than the Nernst filament. Also, when properly seasoned, it has been found to give the desired constancy in composition and intensity of light. As used in these experiments the lamp was operated at 18 amperes, direct current.

The lamp is so constructed that direct radiations from the filament cannot be used satisfactorily for the illumination of the slit of the spectroscope. An image of the same size and shape as the filament was therefore focussed on the slit by two lenses, L_1 and L_2, of the same focal length, 10 cm., one acting as a collimating, the other as a focussing lens. This image served to fill the slit completely and to give a uniform illumination of the face of the prism.

The lenses were amounted in proper alignment on a heavy metal bar continuous with the collimator arm of the spectroscope. The lamp and lens L_1 were enclosed by a metal housing in the anterior wall of which had been cut a circular aperture, 7 cm. in diameter, to permit of the emergence of the collimated beam of light. The housing was painted mat black inside and outside and was provided with light-proof ventilators. The focussing lens L_2 was mounted 8 cm. in front of the aperture of the lamp house.

The weight of the lamp with the auxiliary housing and lenses made it advisable to provide additional support to prevent undue strain on the collimator arm. This was accomplished by extending a rod from a point directly under the center of the lamp house to the table. A ball and socket castor on the lower end of this rod, travelling over the smoothly surfaced table top, gave a minimum of impedance to the rotation of the collimator arm. The

lamp was connected in series with two rheostats, and a Weston ammeter graduated to 0.25 amperes. One of the rheostats was used to produce gross changes of current; the other, to compensate for small fluctuation in the line.

2. *The Spectroscope.*

A diagrammatic representation of the spectroscope is shown in Fig. 3. S_1 is the collimator slit; L_3 the collimating lens; Pr the prism; L_4 the objective lens; S_2 the objective slit; and L_5 and L_6, auxiliary lenses used to focus the light on the eye.

The length of the collimator slit was 12 mm.; the width, 1.05 mm. The width of the slit was kept constant throughout the experiment. A comparatively wide slit, was needed in order (1) that the energy measurements might be made with precision, and (2) that the light intensities obtained should be sufficiently high to meet the somewhat unusual requirements of the experiment.

The objective slit, S_2, was 0.342 mm. in width and adjustable in height. The full height of 10.4 mm. was used for the radiometric measurements in order that an intensity sufficiently high for the energy measurements might be obtained. For the presentation of the light to the eye a much shorter slit was needed. That is, the image which was focussed on the eye had to fall entirely within the pupil. To satisfy this requirement the height of the slit was reduced to 1.85 mm.

The collimator and objective lenses were Zeiss triple achromats, 60 mm. in diameter, with focal lengths of 180 mm. and 240 mm. respectively. The prism, Pr, was 100 mm. high. The length of the refracting base was 115 mm. and the refracting angle was 60°. Because of its large size a liquid (CS_2) prism was used. In order to guard against changes in the refractive index, great care was exercised to keep the CS_2 free from impurities and to maintain the temperature of the room as constant as possible.

Minimum deviation for all wave-lengths falling on the objective slit was obtained automatically by means of an attachment designed specially for the purpose. This device may be

described as follows: K (Fig. 3) " is a rod fastened to the prism table in such a position as to be continuous with the radius of the table which bisects the refracting angle of the prism; X and Y are two rods of equal length fastened at one end to the two arms of the spectroscope at points equidistant from the center of the prism table, and at the other to a collar Z, which is free to play back and forth along rod K. M is a micrometer screw with a graduated head which is used to move the collimator arm through the small angles needed to change the wave-length. Opposite this screw is a plunger working against a spring. The collimator arm is held between the screw and the plunger so that it responds to a movement of the screw in either direction. By this attachment the prism is always turned through half the angle traversed by the collimator arm in changing the wave-length. Therefore, if the prism is once set for minimum deviation for the D-line, there will also be minimum deviation for any other wave-length. That is, when the prism is set for minimum deviation, the line bisecting the refracting angle of the prism also bisects the angle made by the incident and emergent rays; hence if in changing the wave-length the angle between the incident and emergent rays be changed a given amount by a movement of the collimator arm, the prism must be moved through half that angle in order that the line which bisects its refracting angle will also bisect the angle made by the incident and emergent rays."[1]

The wave-length of the light falling on the objective slit was determined by means of a small Hilger direct vision spectroscope calibrated for wave-length. Care was taken to check the wave-length at frequent intervals during each period of work.

In any quantitative work on retinal sensitivity it is very important that the light employed be as homogeneous as possible as to wave-length. Determinations made in this laboratory without provisions for absorbing impurities due to scattered light, internal reflection, etc., show differences large enough to be considered significant. The aim in this study has been to obtain a degree of

[1] M. M. Monroe, The energy value of the minimum visible chromatic and achromatic for different wave-lengths of the spectrum, *Psychol. Monog.*, 1925, **58**, 17–18.

purity such that any part of the spectrum used shows only one band of homogeneous color when examined by a second spectroscope. That this degree of purity might be obtained, the following precautions were observed: All stray light and internal reflections were eliminated so far as was possible by enclosing all light sources and by blackening every surface that might reflect or admit extraneous light into the path of the refracted beam. The light from the room was excluded by completely enclosing the spectroscope and auxiliary optical system in a light-proof compartment. Even with these precautions, however, some impurities remained, chiefly due to reflections from the surface of the lenses. These residual impurities, found in the spectrum produced by every lens-prism spectroscope, were absorbed by very thin gelatine filters selected so as to cut out the alien wave-lengths and reduce the useful light as little as possible. These filters were held in place over the objective slit by small metal clips fastened to the plate containing the slit. The filters were used both for the radiometric measurements and for the threshold determinations.

3. *The Auxiliary Optical System.*

The method of presenting the spectrum light to the eye has already been described in several publications from this laboratory (80, 81, 82). A very brief description only will be given here. The light emerging from the objective slit S_2 was collimated by the lens L_5 and then focussed directly upon the eye by the lens L_6. This latter lens had a focal length of 275 mm.

The principle employed in this system is the same as that used when the eye is placed at the objective slit of the spectroscope. That is, when the eye is placed at the principal focus of a convex lens receiving parallel rays of light, the lens appears to fill uniformly with light. The principle has been modified, however, to give a better control of conditions and a wider range of serviceability than is attained when the eye is placed at the slit of the spectroscope. Instead of placing the eye at the slit, a lens, L_5, is placed at its focal length from the slit and the parallel beam thus obtained is focussed on the pupil of the eye by a second lens,

L_6. The latter lens, therefore, is seen uniformly filled with light and the colored field which it presents is diaphragmed down to the desired size by a circular opening in the screen Sc. Among the advantages gained by this method of obtaining the stimulus field, the following may be noted: (1) So controlled, the amount of light entering the eye may more easily and conveniently be made independent of variations in the size of the pupil than by placing the eye at the objective slit of the spectroscope. (2) The variable effects of brightness of preexposure and surrounding field may be eliminated. (3) Ample room is provided for inserting in the path of the beam the apparatus which is needed for reducing the intensity of light or for other purposes which may be required. And (4), so supplemented the spectroscope may be used in connection with the rotary campimeter for the investigation of the sensitivity of any part of the retina, central or peripheral.

The screen Sc. noted above was located at a distance of 25 cm. from the eye. At the center of this screen is a circular aperture 5.627 mm. in diameter. At 25 cm. from the eye this opening subtends a visual angle of 1°16′. This size of stimulus was used throughout the investigation. The screen is part of a rotary campimeter. It is designed to rotate on a collar around a circular support, thus adding to the vertical campimeter the features of the perimeter. To this collar, the back surface of which is graduated from 0°-360°, are attached the radiating arms of the framework. One of these arms carries the device used for the control of fixation, also a right-angled extension which allows the fixation to be taken at an eccentricity of 110°. This arm can be rotated any desired amount and its angular position be read on the scale. Also a given position can at any time be duplicated with ease and precision. An apparatus of this kind permits of a point by point investigation in every meridional quadrant in the field with as much accuracy and convenience as was possible before with the old form of campimeter in the temporal quadrant alone, or at most in the temporal and nasal quadrants. For a detailed description of the campimeter and the method of using it with

spectrum light, the reader is referred to articles by Ferree and Rand, " Description of a Rotary Campimeter," *Amer. J. Psychol.*, July 1912, 23, pp. 449–453; and "A Spectroscopic Apparatus for the Investigation of the Color Sensitivity of the Retina, Central and Peripheral," *J. Exper. Psychol.*, June, 1916, 1, no. 3, 247–283.

The dimensions of the image focussed on the eye were 3.596 mm. x 0.7463 mm. They were determined by photographing the image on a plate mounted in the plane of the pupil and measuring the image with a micrometer comparator.

The position of the eye at the focal point of the lens L_6 was fixed by having the observer bite a mouth-board on which the impression of her teeth had been previously made and hardened in wax. For convenience of adjustment, this mouthbit was mounted on a support which could be shifted by a screw adjustment backward and forward, up and down, and right and left. The mounting of the mouthbit on the support was such as to permit of swivel movements about the horizontal and vertical axes. Any position of the bit in the vertical and horizontal planes could thus be obtained. This versatility of adjustment of support and bit made it possible always to locate the eye easily and conveniently in the exact position needed to receive the beam of light on the pupil at the proper distance from the screen and to reduce greatly the amount of rotation of the eye required for the more eccentric fixations by a rotation of the head in the same direction. The procedure in making the adjustment was as follows: The head was turned by means of the swivel movements until the desired fixation could be taken with ease and comfort. The eye was then moved by the three-way system of adjustment, right or left, up or down, back or forward, until the stimulus opening was seen to fill evenly and uniformly with light. The support and bit were then securely clamped in position. With these controls the eye could not only be held in a fixed position throughout a given series of observations but could be returned to this position whenever desired. Moreover, both an objective and subjective check on the correctness of the relation

of the position of the eye to the optical system could be had at any time.

Difficulty was encountered in controlling the fixation for threshold determinations with the dark-adapted eye. For determining the threshold for central vision this difficulty was overcome by locating four points just within the margin of the Mariotte spot, two in the vertical and two in the horizontal meridian. These points were located with the eye fixating a point at the center of the field under an intensity of illumination at which such a control of fixation was satisfactory. These points were then covered with luminous paint. As they were just within the margin of the blind spot they were invisible so long as the eye held its proper fixation. A slight movement in any direction, however, was indicated by the appearance of one or more of these points. This device provides not only an extremely sensitive means of detecting inaccuracies of fixation, but also detectors which are invisible during the process of fixation.

It might be supposed that for the peripheral determinations a luminous dot might have been used which could be moved from point to point as the fixation was shifted toward the periphery. It would have been impossible to use such a dot for control of fixation at the center of the field because its presence would have interfered with the determination of the threshold, but for work in the peripheral field this difficulty was not encountered. It scarcely need be pointed out, however, that a luminous dot or point in a dark field provides a very inadequate control of fixation. Moreover, with a dark-adapted eye small luminous dots or patches were found to disappear when fixated and a considerable lapse of fixation, amounting to as much as 1° in any direction, was possible before the point reappeared. A plan for control of fixation was finally adopted similar in principle to the use of the Mariotte spot for the determinations at the center of the field. In this case advantage was taken of the depressed sensitivity at the center of the field which could be made to serve as a blind spot for dots or small patches of very low luminosity. That is, four dots of luminous paint were made on the head of a thumb tack at the corners of a square inscribed in a circle of a diameter of 2°. The

luminous intensity of these dots was made such that when the center of the circle was fixated all were invisible. Any lapse of fixation, however, brought one or more of the dots into view.

The searching movements elicited by the lack of a visible fixation point together with the well-known reflex tendency of the eye to adjust itself to the position of clearest seeing, in this case to bring the luminous points clearly into view by an eccentric fixation, made this method of control difficult at best and one requiring considerable practice before the desired degree of accuracy was obtained. With an adequate amount of practice, however, it proved to be feasible and was, moreover, the only method found which could be made to give a sufficiently accurate and delicate control of fixation under the unusually difficult conditions obtaining in these experiments.

4. *Apparatus for Reducing the Intensity of the Spectrum Light.*

In a study of this type it is necessary to have a means of making both gross and fine changes of intensity. The gross changes are needed to cover the wide range between the smallest value of the threshold and the initial intensity of stimulus required for an accurate measurement of energy. The finer changes are needed for delicacy and precision in making the determinations of the threshold at all levels of sensitivity.

The limiting values of the intensity scale for the different stimuli used are shown in Table 1. In this table are given in watts x 10^{-13} the full intensity of the stimulus used, the lowest value of threshold (achromatic), and the ratios which these values sustain to each other. It was thought to be of interest to include in the table also the highest value of threshold (chromatic), and the ratio of the lowest to the highest values in order to show the wide range of variation in the sensitivity of the retina to radiation. As is seen in the table, the greatest reduction of intensity is needed for the green stimulus, the ratio of the lowest value of the threshold to that of the stimulus being approximately 1 : 83,000,000. The largest ratio of lowest to highest

value of threshold occurs also in the green. Its value is approximately 1 : 6,500,000.

Three devices were used for producing changes of intensity: gelatine filters and a specially prepared set of sectored discs for the gross changes; and a pair of finely graduated gelatine wedges designed to give uniform intensity throughout the cross section of the beam of light, for the finer changes.

The sectored discs. Six discs with fixed open sectors were used. By means of these discs the greater part of the reduction of intensity was made. They were constructed to give trans-

TABLE 1

Showing the limiting values in the intensity scale for the different stimuli employed in the investigation.

Stimulus	Initial intensity of stimulus (watts x 10^{-13})	Highest value of threshold (watts x 10^{-13})	Lowest value of threshold (watts x 10^{-13})	Ratio of lowest value of threshold to initial (numerical value)	Ratio of lowest to highest value of threshold* (numerical value)
Red (672.5 mμ)	858,200	27,140	0.020	1 :42,910,000	1 :1,357,000
Yellow (581.5 mμ)	120,930	6,784	0.00169	1 :71,556,213	1 :4,014,201
Green (522 mμ)	67,090	5,231	0.00081	1 :82,827,160	1 :6,458,025
Blue (468 mμ)	21,660	8,127	0.00368	1 : 5,885,870	1 :2,208,424

*Ratio of highest (red) to lowest (green) value of threshold: 1:33,500,000.

missions of approximately $^1/_4$, $^1/_8$, $^1/_{16}$, $^1/_{32}$, $^1/_{64}$, $^1/_{128}$. The values of the open sectors were measured on a micrometer comparator, and the exact transmission computed from the simple law of the disc. The total values of the sectors for each disc were 90°1′; 45°7′; 22°42′15″; 11°58′; 6°8′; and 3°7′30″ respectively; the transmissions were 25.00 per cent, 12.53 per cent, 6.17 per cent, 3.32 per cent, 1.7 per cent, and 0.87 per cent. The discs were rotated across the beam of light by means of a motor suspended by three coiled springs so attached as to form a three-point support. These springs served both to hold the motor in position and to absorb all disturbing vibrations.

The gelatine filters. The gelatine filters used to supplement the sectored discs for making the gross reductions of intensity were

25 mm. x 25 mm. Their transmissions were approximately ½, ¼, ⅛, and 1/16. These filters were furnished and their density specified by the Eastman Kodak Company. The transmissions were calculated from the formula:

$$\text{Density} = \log [1/\text{transmission}].$$

A holder designed to take any combination of filters up to eight was placed directly in front of the lens L_6. The filters were placed in close contact with the lens in order to preclude the possibility of the passage of any residual stray or scattered light through the opening in the screen to the eye of the observer.

The double wedges. The final reduction of intensity was made by means of the two wedges mounted immediately in front of the objective slit. Obviously, for an accurate determination of the threshold two things are essential: a means must be had of making very small changes of intensity; and the method employed must insure a completely uniform reduction throughout the cross section of the beam of light. A single wedge such as is ordinarily employed, while possibly meeting the first of these conditions does not give the required uniformity of reduction in the cross section of the beam. When placed in front of the slit, no matter how fine the gradations in density, a slight difference in transmission between the opposite edges of the used portion of the single wedge, is unavoidable. The double wedge was designed to obviate this difficulty. These two wedges were made according to specification and calibrated by the Eastman Kodak Company. Like the filters, they were made of neutral tinted gelatine mounted between glass plates. The wedges were identical in size and shape, each measuring 180 mm. x 20 mm., and were so constructed as to cover the same range of transmission. They were mounted parallel to each other in holders operated by a rack and pinion device. This device was so arranged that when the pinion was turned, one rack was engaged by the cogs at the top and the other by those at the bottom. The holders, attached to these racks, were thus caused to move by equal amounts in opposite directions, each wedge travelling past the other through

a path equal, if need be, to twice the length of the wedge, *i.e.*, from a position of juxtaposition at the point of least density at the thin end of each wedge to a position of juxtaposition at the point of greatest density at the thick end of the wedge.

Since the density gradients of the two wedges are identical, and the wedges move in opposite directions, it is obvious that the resulting densities will be the same from point to point throughout the overlapping section. A consideration of the range of movement shows further that a series of densities may be obtained varying by minute amounts from the sum of the minimum densities of both wedges through the sum of the minimum of one and the maximum of the other to the sum of the maxima of both. The density in this case also equals log [1/transmission]. The wedges used in this investigation have a transmission ranging from 82.8 per cent to 25.5 per cent.

As the wedges were well within the light-proof compartment enclosing the spectroscope, they were beyond the reach of the observer. In order that the transmission of the wedges might be varied by the observer while making a threshold determination the following device was used: The pinion which moved the wedges was mounted at one end of a short horizontal rod. At the other end was a sprocket wheel. This sprocket wheel was connected by a chain device to a second sprocket wheel directly beneath, mounted at one end of a long rod which passed under the campimeter screen to a point within easy reach of the observer. At the end of this rod was a small gear with a milled head. When turned, this gear engaged a larger gear on the front of which was mounted a circular plate or dial with a beveled edge. On this edge was a graduated scale calibrated against the linear scale of the wedges. As the density and the percentage transmission of each wedge in relation to this latter scale were known, it was a comparatively simple task to convert the dial readings into percentage transmission of the two wedges. The smallest division of the dial scale corresponded to a change of 0.4 to 0.8 per cent in the intensity of light, while a change of 0.2 per cent could be interpolated with a fair degree of accuracy. These amounts of change were sufficiently below the threshold of dis-

crimination to satisfy fully the requirements of precision in making the determinations over any part of the scale of intensities used in these experiments.

5. *The Radiometric Apparatus.*

The apparatus consisted of a Coblentz linear thermopile; a sensitive Thomson galvanometer especially constructed for use with this thermopile; and various accessories, including a sensitivity tester for the galvanometer, resistance coils to reduce the amount of current from the thermopile, and a reading telescope and scale. For a detailed description of this apparatus the reader is referred to an article by Ferree and Rand: "Radiometric Apparatus for Use in Physiological and Psychological Optics", *Psychol. Monog.*, No. 103, pp. 54–65.

B. Methods and Conditions of Working.

1. *The Radiometric Measurements.*

Measurements were made both at the objective slit and at the eye. The procedure used in making the measurements may be described as follows: "The thermopile to be used was placed in position immediately behind the slit and a blackened aluminum shutter was interposed in the path of the beam of light between the slit and the end of the objective tube of the spectroscope. Preliminary to the exposure of the thermopile to the light to be measured, the current sensitivity of the galvanometer was tested by means of a special device provided for this purpose in the construction of the galvanometer. With regard to this procedure it may be pointed out that the current sensitivity of the galvanometer varies with the period or time of the single swing of its needle system. Since it is not possible to control the field so as to get this period always the same, it is necessary, if results are to be compared, to take some sensitivity as standard and to convert all readings into deflections for the standard sensitivity by means of a correction factor determined at each sitting. (For a detailed description of the method of determining this factor, see *Psychol. Monog.*, No. 103, pp. 60–65.)

"The thermopile was next connected with the galvanometer and the light allowed to fall on its receiving surface until a temperature equilibrium was reached (ca. 3 sec. for our thermopile). The deflections were read by means of the telescope and scale and the readings corrected to standard sensitivity by means of the factor previously determined. The final step in the process of measuring was the calibration of the apparatus, *i.e.*, the value of 1 mm. of deflection in radiometric units was determined for the area of thermopile exposed. To do this a radiation standard, the value of the radiations from which is already known, had to be employed. The standard used by us was a carbon lamp specially seasoned and prepared for the purpose by W. W. Coblentz. This lamp was placed on a photometer bar 2 meters from the thermopile and operated at one of the intensities for which the calibration was made, in our case 0.40 ampere. The thermopile was exposed to its radiations with the same area of receiving surface as was used in case of the lights measured, and the galvanometer deflection was recorded. From the deflections obtained the value of 1 mm. of deflection, or the radiation sensitivity of the apparatus under the conditions given, was computed from the known amount falling on the surface of the thermopile. Having the factor expressing the radiation sensitivity of the apparatus, the deflections produced by the wave-lengths of light measured were readily converted into energy units." (*Psychol. Rev.*, 1919, 26, no. 1, p. 21.)

The radiation sensitivity of the thermopile as used in the present investigation was computed from the following data: The energy value of the radiation from the standard lamp at a distance of two meters, operated at 0.40 amp. of current, was 90.7 watts x 10^{-8} per sq. mm. of receiving surface. The deflection of the galvanometer produced by this intensity of radiation falling on the same area of receiving surface as was used in measuring the lights employed as stimuli, when corrected (a) to a standard sensitivity (i) of 1 x 10^{-10} amp. per mm. of deflection and (b) for the absorption of the glass cover of the thermopile, was 283.87 mm. The area of the surface exposed was 3.557 sq. mm. The sensitivity of the instrument for this area of receiv-

ing surface was, therefore, 113.65 watts x 10^{-10} per mm. deflection. By means of this factor the galvanometer readings produced by the different wave-lengths of light were readily converted into the energy values of the light falling on the receiving surface of the thermopile. For the purpose of the present investigation it was needed to know also the energy value of the light entering the eye. This is sufficiently great only in case of the long wave-lengths of the spectrum to be measured with the required precision. It was necessary therefore to measure all the wave-lengths used at the objective slit and the red or yellow at the eye, and from the comparative energies of the latter at the two places to determine a correction factor which would represent for all the colors the reduction of light from objective slit to eye. In order to determine this reduction factor with precision a larger area of receiving surface of the thermopile had to be exposed to the light than the actual area of the image at the eye. It will be remembered that the height of the objective slit and consequently the height of the image focussed on the pupil of the eye were adjustable. In the present work the receiving surface of the pile used to measure the light at the eye was 0.7366 mm. x 11.138 mm., or 8.204 sq. mm. The value corresponding to 1 mm. deflection of the galvanometer for this area of receiving surface was 96.1 watts x 10^{-10}. Since the focussed image was of uniform density, the energy for the area of the image at the eye, 3.596 mm. x 0.7463 mm., or 2.684 sq. mm., could be readily determined. The reduction factor of the light from the objective slit to the eye was computed from the following data: energy of red radiation at the objective slit, 4872.56 watts x 10^{-8}; at the eye, 35.17 watts x 10^{-8}. The ratio of these two values gives a reduction factor of 130.85. The value 35.17 watts x 10^{-8} was, however, obtained for an exposed area of pile at the eye equal to 8.204 square millimeters, while the area of the focussed image was but 2.684 square millimeters. Therefore, to obtain the energy actually entering the eye, the reading at the objective slit must be divided by $\frac{8.204}{2.684} \times 130.85 = 400.4$.

The values obtained for the total energy at the eye were:

Red	(672.5 mμ),	858.2 watts x 10^{-10}
Yellow	(581.5 mμ),	120.93 watts x 10^{-10}
Green	(522.0 mμ),	67.09 watts x 10^{-10}
Blue	(468.0 mμ),	21.66 watts x 10^{-10}

All energy measurements necessary for the present investigation were made by Dr. Gertrude Rand. For this service the writer wishes to express her thanks and very great indebtedness.

2. *Conditions under Which the Work Was Done.*

As two series of determinations were made, the one with a light-adapted, the other with a dark-adapted eye, the following conditions were necessary.

(a) *Dark Adaptation.* The apparatus was set up in a light-tight dark room, the walls, floor and ceiling of which were painted a mat black. Conditions for complete dark adaptation were further provided for by enclosing both the source of light and the spectroscope with its auxiliary apparatus for presenting the light to the eye in light proof compartments.

(b) *Light Adaptation.* For the work under light adaptation, the screen of the campimeter Sc was illuminated to an intensity of 7 ft.-c. by a 75-watt, bowl frosted, type C_2 Mazda lamp, operated by ammeter and rheostat control. The light from the lamp was directed to the screen by a reflector placed above the head of the observer at such an angle as to give an optimum evenness of distribution of light. The illumination was measured by means of a Macbeth illuminometer, with the test-plate mounted in the vertical plane and centered over the stimulus opening. The component of the illumination measured was thus the component to which the eye was adapted.

The field surrounding the stimulus, and the preexposure were always maintained as nearly as possible at the same brightness as the stimulus at the threshold value of sensation. Hering standard gray papers were used for this purpose. It was found necessary to change the brightness of the surrounding field and preexposure frequently for each stimulus because the bright-

ness value of the color at the chromatic threshold changes quite rapidly from the center to the periphery of the retina. Two reasons for this change may be offered: (1) the intensity of the light necessary to give a chromatic threshold from point to point has to be greatly increased in passing from center to periphery, and (2) the achromatic value of the colors does not remain constant for all parts of the retina. The gray that matched the stimulus in achromatic value at each point was determined by the equality of brightness method. The match was always made for the part of the retina under investigation. The method used was as follows: The threshold was first obtained with no especial control of brightness of preexposure or surrounding field. The brightness of preexposure and surrounding field were then made to match that value of stimulus and the threshold was redetermined. This procedure was repeated until no further change in these surfaces was needed to match the stimulus in brightness at the threshold value obtained. In order to make the specification of the brightness of the preexposure and surrounding field independent of the illumination of the room and of the variability of different issues of the Hering papers, it was expressed in millilamberts, in accordance with the formula:

millilamberts = foot-candles x 1.076 x reflection coefficient

For reproducibility of conditions from time to time and for comparative work in various laboratories it is obvious that a photometric specification should be given of the brightness of all surfaces for which precision of control is of importance to the results of the work.

3. *The Method of Observation.*

Each series of determinations was preceded by an adaptation period. Forty-five minutes of adaptation in the dark room and thirty minutes in the light room were found to be sufficiently long to give constancy of results.

The observer was seated in front of the apparatus, the eye being at the focal length of the lens L_6. Steadiness of fixation was insured by means of the mouthbit and fixation devices pre-

viously described. The eye not being investigated was lightly covered with a soft black silk patch.

In making the determination the threshold was approached by ascending and descending series. To avoid loss of sensitivity through fatigue or adaptation to the color in question the stimulus opening was covered between judgments by a preexposure card of a gray the brightness of the color at the threshold, and an exposure-time of only one second was used. For each threshold value a number of independent observations [1] were made and the average taken. An average error not greater than 1 to 1.5 per cent was demanded as a limit of precision. The settings of the dial during dark adaptation were read by the observer by means of a small flashlight so covered with black cloth as to give the minimum illumination required to make the reading. A few minutes were allowed after each reading for the eyes to regain its previous level of adaptation.[2] To guard against sensory and general fatigue frequent rest periods were allowed. Also, in order that for comparative purposes the general level of sensitivity might be kept as nearly constant as possible throughout the entire investigation the beginning of each new series of determinations was preceded by checking the results of previous determinations at one or more points. If a change were found the observations were not continued at that time. It is obvious that in a case of this kind where a number of results taken at different times have for any reason to be compared, the same type of precaution has to be applied to the use of the sense organ as is exercised in connection with a galvanometer or other physical recording instrument whose sensitivity is liable to vary from time to time.

[1] In general four or five independent observations were made for each threshold determination. As many as seven or eight and as few as three were made occasionally, however, depending upon the variability of the settings obtained and the subjective difficulty of the observations.

[2] That this level was not seriously disturbed by the short exposures to dim light required to make the readings was assumed on the basis of constancy of the readings obtained by this method and the statements made by Parsons, Charpentier, and others that momentary exposures to *bright* light affect the curve of dark adaption only temporarily.

IV. RESULTS.

Before proceeding to the detailed discussion of the results of the investigation, a brief survey of the data to be presented will be given.

I. In the form of tables.

(a) The amounts of energy required to arouse the chromatic threshold sensation for the four spectrum stimuli, light adaptation (Tables 2–9); the chromatic thresholds, dark adaptation (Tables 14–17); the achromatic thresholds, dark adaptation (Tables 20–21). Included in the tables for chromatic thresholds are the hue changes which occur in the threshold sensation from point to point; and in the tables for light adaptation, the brightness in millilamberts of the surrounding field and preexposure used. The latter furnishes an approximate measure of the brightness of the stimulus of threshold value, since at each point investigated under light adaptation the brightness of the surrounding field and preexposure was matched as nearly as possible to the threshold sensation. The thresholds were obtained at near-lying points from center to periphery of the field in several meridional quadrants.[1]

(b) Chromatic sensitivity, light adaptation (Table 10); chromatic sensitivity, dark adaptation (Table 18); achromatic sen-

[1] In these and other results given in this study reference of the points investigated is made to the field of vision rather than to the retina because it is impossible to determine for any given point in the field of vision what the corresponding point on the retina is without a knowledge of the net displacement, if any, of the image toward the principal axis of the refracting system as the beam of light enters the eye more and more obliquely. The factors contributing to such displacement are difficult to determine in a refracting system so complex as that of the eye. However, the difference in optical density of the media traversed by the incident and emergent ray, the greater combined refracting power of the cornea and anterior surface of the lens than of the posterior surface of the lens, and the curvature of the cornea, which varies widely for different eyes, may well be taken into account.

A consideration of the above factors, particularly of the last, is of help also in explaining the great width of the temporal field which extends to 95°

sitivity, dark adaptation (Table 22). In these tables, sensitivity is represented as the reciprocal of the energy required to arouse the threshold sensation. Included also are ratios of sensitivity to the different colors when the maximum sensitivity at each point is taken as unity.

(c) Values of the photochromatic interval for the different colors from center to periphery and the relative value when the maximum value of the interval is taken as unity (Tables 23–25).

(d) Areas of the color fields for stimuli equalized in energy at different levels of intensity (Tables 11–13).

II. In the form of graphs.

(a) Threshold Curves: chromatic thresholds, light adaptation (Figs. 4–7); chromatic thresholds, dark adaptation (Figs. 35–36); achromatic thresholds, dark adaptation (Figs. 39–42). Each curve in these charts represents two quadrants so arranged as to form a complete cross section of the field of vision from periphery to periphery through the center of the field. Degree of eccentricity is plotted along the abscissa and value of the threshold sensation in watts (10^7 ergs per sec.) along the ordinate. In Figs. 8 and 9, the chromatic thresholds, light adaptation, are shown for each color in the eight quadrants investigated.

(b) Sensitivity Curves: chromatic sensitivity, light adaptation (Figs. 10–11); chromatic sensitivity, dark adaptation (Fig. 37); chromatic sensitivity, light vs. dark adaptation (Figs. 47–50); achromatic sensitivity, dark adaptation (Fig. 43). In these charts, degree of eccentricity is plotted along the abscissa and sensitivity (reciprocal of the threshold value in watts) along

or even 100°, *i.e.*, an object 5° or even 10° back of the plane tangent to the anterior surface of the cornea at or near the point of intersection with the line of regard, is still visible. This wide extension of the field of vision on the temporal side has been reported by a number of investigators. DeSchweinitz, for example, quotes Baas as obtaining an average limit of 99°; Ferree and Rand with carefully controlled fixation found the limits to extend as far as 92°; and the writer in several hundred perimetric studies made under standard conditions in which the fixation was so carefully controlled that no shifting could be detected, found limits of 95° and even 100° to occur frequently.

the ordinate. Another type of sensitivity curve is given in Fig. 12. It takes the form of a four-point curve of threshold sensitivity plotted for selected points in the temporal quadrant. These curves show the relative sensitivity of different parts of the retina to the four colors when the maximum sensitivity at each point is taken as unity.

(c) Photochromatic Interval (Figs. 44–46).

(d) Limits of sensitivity to the four colors at nine levels of intensity of stimulus (Figs. 13–25); limits of sensitivity to red of a given intensity and to blue of intensities that give smaller, larger and interlacing limits (Figs. 28, 30, 32); limits of sensitivity to blue at a given intensity and to red of intensities that give smaller, larger and interlacing limits (Figs. 29, 31, 33); limits of sensitivity to blue of a given intensity and to green of intensities that give smaller, larger and interlacing limits (Fig. 34); limits of sensitivity to standard pigment colors and to spectrum colors of known energy which give limits most nearly approximating those for the pigments (Fig. 27); variation in extent of color fields with log intensity of stimulus (Fig. 26).[1]

The data presented in these tables and charts have been combined and arranged in order that the following comparisons may be made:

(1) Chromatic sensitivity to a given range of wave-lengths from point to point in the same meridian, light adaptation.

(2) Chromatic sensitivity to the different wave-lengths in any given meridian, light adaptation.

[1] The relation of the various types of charts and curves to each other may perhaps be clarified somewhat if the field of vision is regarded as an island rising to different levels of sensitivity. The charts may then be considered as horizontal or vertical sections of this island. The sensitivity curves are the contour lines for the vertical sections passing across the island in different radial directions but always through its center, while the diagrams for the limits of sensitivity outline horizontal sections taken at different altitudes. In the vertical section the sensitivities to different colors are seen to rise to different levels, giving the effect of strata the thicknesses of which vary from point to point. Finally the curves showing the comparison of sensitivities to the different colors at different degrees of eccentricity outline vertical sections made at right angles to the long radial sections.

(3) Chromatic sensitivity to a given range of wave-lengths at corresponding points in the different meridians, light adaptation.

(4) Achromatic and chromatic sensitivity to a given range of wave-lengths from point to point in a given meridian, dark adaptation.

(5) Achromatic and chromatic sensitivity to the different wave-lengths in any given meridian, dark adaptation.

(6) The relation of achromatic to chromatic thresholds, *i.e.*, the photochromatic interval, for a given range of wave-lengths from point to point in the same meridian, dark adaptation.

(7) Chromatic sensitivity to a given range of wave-lengths in any given meridian for the light and the dark-adapted eye.

(8) Limits of chromatic sensitivity for a given range of wave-lengths at different levels of intensity.

(9) Limits of chromatic sensitivity for the different wave-lengths at the same level of intensity.

(10) Graphic relationship of intensity of stimulus to area of field for the different stimuli.

TABLES 2—9

CHROMATIC THRESHOLDS, LIGHT ADAPTATION

Showing the energy values of spectrum lights at the eye required just to arouse the chromatic sensation at near-lying points from center to periphery in the temporal and nasal quadrants of the 180° meridian, the upper and lower quadrants of the 90° meridian, and the four quadrants of the 45° meridians. In these tables are included also the brightness of the prexeposure and surrounding field in ml. and the hue changes that occur in the threshold sensation.

CHROMATIC THRESHOLDS—(LIGHT-ADAPTED EYE)

TEMPORAL QUADRANT—180° MERIDIAN

Degrees Eccentricity in Field of Vision	Amount of Light Entering Eye (Watts x 10^{-13})				Brightness of Preexposure and Surrounding Field (millilamberts)				Changes in Threshold Sensation			
	Yellow $\lambda=$ 581.5 mμ	Blue $\lambda=$ 468 mμ	Green $\lambda=$ 522 mμ	Red $\lambda=$ 672.5 mμ	Yellow $\lambda=$ 581.5 mμ	Blue $\lambda=$ 468 mμ	Green $\lambda=$ 522 mμ	Red $\lambda=$ 672.5 mμ	Yellow $\lambda=$ 581.5 mμ	Blue $\lambda=$ 468 mμ	Green $\lambda=$ 522 mμ	Red $\lambda=$ 672.5 mμ
0°	1.9349	3.0324	3.4667	6.8656	0.1054	0.1054	0.1054	0.1054	reddish brown-yellow	gradual increase in brightness	gradual increase in brightness	very dark red
5°	1.9345	3.7255	5.6356	6.8656	do	do	do	do				do
10°	1.9345	6.2815	5.6356	7.7238	do	do	do	do				do
13°	2.0558	6.2815	5.6356	8.5820	do	do	do	do				do
B. S.												
19°	6.0465	11.2632	8.7217	9.4402	do	do	do	do				do
20°	6.0465	11.2632	8.7217	11.1566	do	do	do	do				deep red
25°	6.0465	10.6114	16.1016	12.8730	do	do	do	do				do
30°	9.6744	19.7106	21.2004	13.8212	do	do	0.2560	do				do
35°	12.0930	19.7106	19.3219	14.5984	do	do	do	do				red
40°	15.7209	28.8078	31.6665	16.3058	do	do	do	do				do
43°	..	28.8078	..	..	..	do	..	..				..
45°	14.5126	37.2552	37.1008	18.0222	do	do	do	do				do
50°	16.9302	49.8180	52.4644	26.6042	0.2560	0.2560	0.3269	0.2560				orange-red
55°	27.8139	54.5832	62.7291	28.3206	do	do	do	do				do
60°	31.4418	62.3808	70.1761	47.2010	do	do	do	do				do
63°	37.4803	..	..	..	do	..	..	..				do
65°	38.6976	120.8428	102.6477	66.9396	0.4662	0.3959	do	do				do
67.5°	37.4803	..	..	..	do	..	..	..				do
70°	33.8604	139.2738	115.1935	68.6560	do	0.7781	0.3939	do				do
75°	39.9069	201.6546	143.7068	120.148	do	do	do	do				do
80°	85.8603	265.1184	154.5754	154.476	0.9340	0.9340	1.1675	0.3269				yellow-orange
85°	96.7440	430.8174	231.8630	317.534	2.2295	do	do	0.3939		very light blue		orange-yellow
89°	..	1142.0210	..	..	..	5.1519	..	..				do
90°	252.7437	3002.5092	631.1156	5346.586	do	do	2.2295	0.9340				do
93°	..	..	1528.3120	..	..	..	5.1519	..		blue-white (shade of blue diamond	yellow	do
95°	978.8818	6520.5164	..	17018.106	do	do	..	do				do
100°	6784.1730	..	..	20906.752	do	..	..	do				mostly yellow slight orange tinge

gradual change thru orange-yellow to very light yellow

TABLE 3

CHROMATIC THRESHOLDS—(LIGHT-ADAPTED EYE)

NASAL QUADRANT—180° MERIDIAN

Degrees Eccentricity in Field of Vision	Amount of Light Entering Eye (Watts x 10^{-13})				Brightness of Preexposure and Surrounding Field (millilamberts)				Changes in Threshold Sensation			
	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ
0°	1.9349	3.0324	3.4667	6.8656	0.1054	0.1054	0.1054	0.1054	reddish brown-yellow	gradual increase in brightness	gradual increase in brightness	dark maroon
5°	2.1767	3.2490	3.8912	7.7238	do	do	do	do	gradual change orange-yellow to canary-yellow			red
10°	2.1767	4.1194	4.1596	17.164	do	do	do	do				do
15°	2.9023	12.5628	9.2242	17.164	do	do	do	do				do
20°	3.6279	25.1256	38.0400	17.164	do	do	0.2560	do				red-orange
25°	6.0465	25.7774	42.8705	34.328	do	do	do	do				do
30°	7.2558	30.7572	46.2400	34.328	do	0.2560	do	do				orange
35°	7.2558	67.1460	67.0900	51.492	do	do	do	0.2560				brown-red
40°	29.0232	98.3696	79.8371	137.312	0.4662	do	do	do				do
45°	39.9069	185.8428	84.3992	197.386	do	7.035	0.4662	do				red
46°	..	371.4690	..	..	..	do	..	..				
48°	..	916.4346	..	..	..	do	..	..				
50°	68.9301	899.1066	96.9451	901.110	1.1675	1.2352	0.9340	0.3269				do
52.5°	..	510.7428	..	..	..	do	..	..				
55°	78.6015	348.2928	316.3964	1433.194	do	do	do	0.3939				orange-red
57.5°	..	609.5124	..	..	..	1.6947	..	..				
60°	269.6739	731.4582	826.5488	2814.896	6.4926	do	2.2295	0.9340				red-orange
62°	732.8358	4814.3682	1978.3157	6788.360	do	2.8848	6.4926	do				orange-yellow

TABLE 4

CHROMATIC THRESHOLDS—(LIGHT-ADAPTED EYE)

UPPER QUADRANT—90° MERIDIAN

Degrees Eccentricity in Field of Vision	Amount of Light Entering Eye (Watts x 10^{-13})				Brightness of Preexposure and Surrounding Field (millilamberts)				Changes in Threshold Sensation			
	Yellow $\lambda=$ 581.5 mμ	Blue $\lambda=$ 468 mμ	Green $\lambda=$ 522 mμ	Red $\lambda=$ 672.5 mμ	Yellow $\lambda=$ 581.5 mμ	Blue $\lambda=$ 468 mμ	Green $\lambda=$ 522 mμ	Red $\lambda=$ 672.5 mμ	Yellow $\lambda=$ 581.5 mμ	Blue $\lambda=$ 468 mμ	Green $\lambda=$ 522 mμ	Red** $\lambda=$ 672.5 mμ
0°	1.9349	3.0324	3.4664	6.8656	0.1054	0.1054	0.1054	0.1054	reddish brown-yellow	gradual increase in brightness	graduat increase in brightness	dark maroon red
5°	2.0558	3.0324	4.4279	8.5820	do	do	do	do				do
9°	..	..	..	15.4476	..	..	..	do				do
10°	2.2977	9.0972	6.9774	42.9100	do	do	do	do	gradually changing to			do
12°	..	..	..	25.7460	..	..	..	do				orange-red
15°	2.6616	28.3746	8.1850	14.5894	do	do	0.2560	0.2560	more orange			do
20°	2.7824	29.4576	17.9801	17.1640	0.2560	0.2560	do	do				.get green-yellow
25°	7.8605	35.3058	24.1524	24.0296	do	do	do	0.3269	gradually changing to			.beforeredappears
30°	10.4000	53.0670	161.9553	68.6560	do	do	0.3939	do				.very light orange
35°	28.9232	98.7696	190.8040	120.148	0.4662	0.3269	do	do				.nearly colorless
40°	34.3541	124.7616	233.6745	1047.004	0.7035	0.3939	1.1675	do	yellow-orange			. yellow orange
45°	74.9766	464.3904	320.2206	1604.834	do	2.8848	2.2295	do	bright yellow	very light blue		yellow-orange
50°	85.3766	708.2820	458.6943	3398.472	0.9340	do	do	do	do			orange
55°	483.5991	3157.8114	1005.3437	5749.940	2.2295	do	do	0.3939	do			

TABLE 5

CHROMATIC THRESHOLDS—(LIGHT-ADAPTED EYE)

LOWER QUADRANT—90° MERIDIAN

Degrees Eccentricity in Field of Vision	Amount of Light Entering Eye (Watts x 10^{-31})				Brightness of Preexposure and Surrounding Field (millilamberts)				Changes in Threshold Sensation			
	Yellow $\lambda=$ 581.5 mμ	Blue $\lambda=$ 468 mμ	Green $\lambda=$ 522 mμ	Red $\lambda=$ 672.5 mμ	Yellow $\lambda=$ 581.5 mμ	Blue $\lambda=$ 468 mμ	Green $\lambda=$ 522 mμ	Red $\lambda=$ 672.5 mμ	Yellow $\lambda=$ 581.5 mμ	Blue $\lambda=$ 468 mμ	Green $\lambda=$ 522 mμ	Red $\lambda=$ 672.5 mμ
0°	1.9349	3.0324	3.4667	6.8656	0.1054	0.1054	0.1054	0.1054	gradual change from reddish yellow thru orange-yellow to yellow	dark purple-blue	gradual increase in brightness	dark maroon gradually changing to
5°	2.2977	3.0324	4.6963	6.8656	do	do	do	do				red-orange
10°	2.2977	6.0648	7.1115	8.582	do	do	do	do				do
15°	2.2977	11.6964	17.1750	10.2984	do	do	do	do				do
20°	2.4196	28.3746	19.3219	13.7312	do	do	do	do				do
25°	2.5405	29.0244	22.2739	17.164	do	0.2560	0.2560	do				do
30°	2.9033	32.4900	33.0754	17.164	0.2560	do	do	do				do
35°	4.1116	36.1722	47.3655	25.746	do	do	0.3269	0.2560				do
38°	..	81.8748	..	..	..	0.3269	..	..				do
40°	4.4744	129.5268	85.5398	32.6176	do	do	do	do				do
42°	..	96.6036	..	..	..	do	..	..				do
44°	..	77.1096	..	..	..	do	do	..			yellowish-green	do
45°	8.4651	72.5610	108.3503	33.4698	do	do	0.3939	do			very yellow green	red-orange
50°	38.2139	74.9436	118.8164	51.492	0.4662	do	do	do				do
55°	48.3720	81.0044	212.5411	77.238	do	do	0.7796	do				do
60°	59.6185	113.9316	352.6250	85.820	do	0.3939	do	do				do
65°	126.4928	136.4580	372.1482	128.730	0.7035	do	0.9340	do				do
70°	383.1062	499.0464	527.9312	901.110	0.9340	0.7035	do	do				do
75°	507.0595	615.3606	688.3434	3449.964	do	0.9340	1.1675	0.7035				do
80°	949.7842	1822.6890	2822.8118	9443.184	do	2.7341	5.1519	do				do

TABLE 6

CHROMATIC THRESHOLDS—(LIGHT-ADAPTED EYE)

UPPER TEMPORAL QUADRANT—135° MERIDIAN

Degrees Eccentricity in Field of Vision	Amount of Light Entering Eye (Watts x 10^{-13})				Brightness of Preexposure and Surrounding Field (millilamberts)				Changes in Threshold Sensation			
	Yellow $\lambda=$ 581.5 mμ	Blue $\lambda=$ 468 mμ	Green $\lambda=$ 522 mμ	Red $\lambda=$ 672.5 mμ	Yellow $\lambda=$ 581.5 mμ	Blue $\lambda=$ 468 mμ	Green $\lambda=$ 522 mμ	Red $\lambda=$ 672.5 mμ	Yellow $\lambda=$ 581.5 mμ	Blue $\lambda=$ 468 mμ	Green $\lambda=$ 522 mμ	Red $\lambda=$ 672.5 mμ
0°	1.9349	3.0324	3.4667	6.8656	0.1054	0.1054	0.1054	0.1054	red-brown yellow	deep blue	green	dark maroon
5°	2.0558	4.5486	5.2330	6.8656	do	do	do	do	very reddish yellow	do	do	deep red
10°	2.1767	9.0972	6.2394	8.5820	do	do	do	do		do	do	
15°	2.5405	10.1802	8.3192	9.4462	do	do	do	do		do	very blue-green	gradually changing to
20°	2.5405	21.4434	16.1016	14.5894	do	do	0.2560	do	good yellow	very dark blue	yellow-green	
25°	3.1279	23.6294	17.7118	16.3058	do	do	do	do	slightly greenish	gradually changing to	gradual increase in brightness	yellow-bronze red
30°	7.9814	35.0892	20.3954	31.7524	0.2560	0.2560	do	0.2560				to
35°	9.4325	36.8220	34.2159	30.9952	do	do	do	do				red-orange
40°	31.4418	45.2694	38.2413	36.0444	do	do	do	do				to
45°	31.9255	47.8686	68.4318	66.9396	do	0.3939	do	do				orange-yellow
50°	33.8604	71.6946	93.5235	96.7258	0.4662	do	0.3939	do				
55°	60.7069	77.9760	101.5072	108.4316	do	0.7035	do	do		very light gray-blue		
60°	68.9302	81.0084	140.2852	208.5426	do	0.7781	0.7035	do		light blue		
65°	120.3254	113.9316	171.4820	248.0198	0.7035	1.1675	do	do		do		
70°	123.3486	124.7616	185.9735	299.5118	0.9340	1.6947	1.1675	0.3269		very light blue		
75°	152.1299	311.4708	362.2860	568.9866	do	2.8848	2.2295	do		nearly white		
80°	322.1685	596.9496	406.7667	845.9852	do	5.1519	do	do		do	very light	very slight
85°	402.6969	1041.4128	1905.8897	3449.9641	1.1675	do	5.1519	0.3939		do	yellow-green	orange tinge
90°	2754.7854	3313.1136	2305.2438	5286.5120	2.2295	do	do	0.9340		do		
93°	..	8127.4818	..	..	..	do	..	..	very light yellow	do	yellow	yellow
95°	5348.6130	..	..	27139.7168	16.4926	..	do	..		do		

TABLE 7

CHROMATIC THRESHOLDS—(LIGHT-ADAPTED EYE)

LOWER NASAL QUADRANT–135° MERIDIAN

Degrees Eccentricity in Field of Vision	Amount of Light Entering Eye (Watts x 10^{-13})				Brightness of Preexposure and Surrounding Field (millilamberts)				Changes in Threshold Sensation			
	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ
0°	1.9349	3.0324	3.4667	6.8656	0.1054	0.1054	0.1054	0.1054	gradual change from reddish-orange to light yellow	gradual increase in brightness	gradual increase in brightness	dark red
5°	1.9349	3.2490	3.9583	7.7238	do	do	do	do				red
10°	1.9349	7.1478	3.7570	8.582	do	do	do	do				do
15°	1.9349	11.2632	4.1596	17.164	do	do	do	do				orange
20°	1.9349	24.2592	6.3736	17.164	do	0.2560	do	do				brown-red
25°	2.5405	25.7754	22.9443	22.3132	do	do	0.2560	do				light brown-red
30°	8.9488	31.6236	24.6891	25.746	do	0.3269	do	do				do
35°	11.0046	31.6236	50.9884	31.8534	0.2560	do	0.3269	0.2560				orange-red
40°	12.8186	67.1460	73.7990	31.8534	do	0.3939	0.4662	do				do
45°	39.6741	85.7736	265.6764	60.074	0.4662	do	0.7035	do				do
50°	45.4797	98.9862	354.8390	68.646	do	do	1.1675	do				do
55°	78.1208	103.1016	588.7148	111.566	0.7193	do	2.2295	do				light red
60°	158.3074	225.2640	2750.9584	231.714	do	0.9340	do	do				red
63°	352.6319	..	..	..	do	..	..	..				do
64°	1154.6387	..	..	..	1.1675	..	..	..				do
65°	2318.2281	3520.1832	..	4763.010	do	do	..	0.9340				deep orange -yellow

TABLE 8

CHROMATIC THRESHOLDS—(LIGHT-ADAPTED EYE)

LOWER TEMPORAL QUADRANT—45° MERIDIAN

Degrees Eccentricity in Field of Vision	Amount of Light Entering Eye (Watts x 10^{-13})				Brightness of Preexposure and Surrounding Field (millilamberts)				Changes in Threshold Sensation			
	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ
0°	1.9349	3.0324	3.4667	6.8656	0.1054	0.1054	0.1054	0.1054	reddish brown-yellow	gradual increase in brightness	gradual increase in brightness	dark maroon
5°	2.0558	2.8148	7.8495	6.8656	do	do	do	do				red
10°	2.0558	3.8998	8.3863	8.582	do	do	do	do	do			do
15°	1.9349	10.8300	16.3780	11.1566	do	do	do	do	very reddish-			do
20°	2.0558	11.9130	24.6891	11.1566	do	do	do	do	yellow			do
25°	2.0558	21.4434	32.4716	12.0148	do	do	do	do	gradually			orange-red
30°	3.7488	22.0932	36.4970	17.164	do	do	0.2560	do	changing			orange
35°	5.0791	32.4900	45.0845	17.164	0.2560	0.2560	do	do	to			do
40°	8.3441	33.1398	55.8950	25.746	do	do	do	do	more greenish			do
45°	7.4977	37.4718	76.4155	28.3206	do	do	do	do	yellow			yellow-orange
50°	7.9814	43.7532	98.0856	29.1788	do	do	0.3269	do			very yellow	bronze-red
55°	16.9302	44.4030	104.9287	32.6166	do	do	do	0.2560	gradually changing	very bright blue	green blue-green	orange
60°	37.2464	44.4030	123.1772	51.492	0.4662	do	0.3939	do	to		do	do
65°	50.3069	51.5508	164.2363	77.238	do	0.3269	0.7035	do			green	red
70°	54.1760	89.8892	200.4649	120.148	do	do	do	do	pure yellow	do	do	do
75°	57.5627	101.5854	212.5411	231.714	1.1675	do	0.7781	0.3269		do	do	yellow-orange
80°	67.8417	121.9458	212.5411	883.946	do	0.3939	0.9340	do		do	yellow-green	orange-yellow
85°	105.9347	205.9866	458.6943	1252.972	do	0.7035	1.1675	0.3939		do	very light yellow-green	deep-orange- yellow
90°	600.7802	615.3606	1168.3724	3338.398	do	1.1675	2.2295	0.7035	gradual increase in brightness	do	.goes yellow almost instantly after threshold obtained	
92°	..	..	5231.6111	..	..	..	5.1519	..				
95°	979.5330	6604.5672	..	8959.608	2.2295	..	..	0.9340	very light		yellow	orange-yellow
100°	2625.1484	..	..	22828.120	6.4926	..	..	do	almost white			do

TABLE 9

CHROMATIC THRESHOLDS—(LIGHT-ADAPTED EYE)

UPPER NASAL QUADRANT—45° MERIDIAN

Degrees Eccentricity in Field of Vision	Amount of Light Entering Eye (Watts x 10^{-13})				Brightness of Preexposure and Surrounding Field (millilamberts)				Changes in Threshold Sensation			
	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ
0°	1.9349	3.0324	3.4667	6.8656	0.1054	0.1054	0.1054	0.1054				dark maroon
5°	1.9349	3.2490	4.6292	6.8656	do	do	do	do				do
10°	1.9349	4.1154	5.2330	17.164	do	do	do	do				dark purple-red
15°	2.1767	12.5628	8.1850	17.164	do	do	do	do			very yellow-green	
20°	2.1767	25.1256	19.3219	25.746	do	do	do	do				red
25°	4.1116	25.7754	27.1715	32.611	0.2560	do	0.2560	do				do
30°	6.6512	30.7572	36.8324	36.044	do	0.2560	do	do				orange-red
35°	29.9906	67.1460	73.7990	51.492	do	do	0.4662	do				brown-red
40°	33.8604	98.3696	85.8752	446.264	do	do	0.9340	do				yellow-orange
45°	40.6325	185.8428	85.8752	600.740	0.4662	0.7035	do	do	gradual change from reddish brown yellow to light yellow	gradual increase in brightness	gradual increse in brightness	do
46°	..	371.4690	..	..	..	do	..	..				
48°	..	916.4346	..	..	..	do	..	..				
50°	57.5627	899.1066	118.6151	901.110	do	1.2352	1.1675	0.2560				do
52.5°	..	510.7428	..	..	..	do	..	..				
55°	141.8509	348.2928	374.3622	1287.300	do	do	do	0.4700				very little orange
57.5°	..	609.5124	..	..	..	1.6947	..	..				
60°	478.8828	731.4582	739.0634	2531.690	0.7193	do	do	do				yellow-orange
62°	1117.3932	4814.3682	3988.2321	4893.158	6.4926	2.8848	do	do				orange-yellow

A. Light Adaptation.

1. *Chromatic Thresholds.*

The chromatic thresholds were determined under light adaptation at near-lying points in the eight principal meridional quadrants: the nasal and temporal quadrants of the horizontal meridian, the upper and lower quadrants of the vertical meridian and the four quadrants of the two 45° meridians. Before any determinations were made the eye was adapted for 30 minutes to an illumination of 7 ft.-c. The method of obtaining and controlling this illumination has already been described.

Since this section of the investigation is a continuation of the study planned and in part carried out by Ferree and Rand, it may be well to repeat here a few selected points of summary of their work.

In 1911 Ferree and Rand outlined a program for the investigation of retinal sensitivity to colored light (7). To render the results directly comparable all measurements of the stimulus were to be made in radiometric units. The study was planned to include a determination of the sensitivity of the peripheral and central retina at near-lying points in a number of meridians to red, yellow, green and blue spectrum lights and a determination of the limits of sensitivity in the different meridians to each of the colors at various levels of intensity. To make it possible to eliminate contrast and after-image effects from surrounding field and preexposure, the investigation was to be made in a light-room, the illumination of which should be so controlled and specified as to be reproducible at any time. All the other variable factors, which had been determined in previous studies, were likewise to be controlled and specified.

In 1915 the results were published for the nasal and temporal quadrants of the horizontal meridian (1), pressure of other work having made it impossible to continue the investigation in the other meridians as planned. In their conclusions the following points are stressed:

(1) the great range of sensitivity from the center to the extreme periphery of the retina;

(2) the irregularities in the curve of sensitivity for the different colors in a given quadrant;

(3) the great difference in sensitivity at corresponding points in the temporal and nasal quadrants, more particularly in the remote portions of the field, from which it was inferred that an interlacing or crisscrossing of limits would be obtained if the stimuli were so graded in intensity as to make the limits for all colors fall in the same general region of the retina;

(4) the striking absence of uniformity of ratio of sensitivity to the pairs of colors, red and green, and blue and yellow from center to periphery of the retina;

(5) the correspondence of the distribution of sensitivity to red, green and yellow with what might be expected from these changes in the color-tone of red and green in passing from the center to the periphery of the retina; and

(6) the small areas blind[1] or very insensitive to one color and normally sensitive to the other three.

The present study repeats their investigation in the nasal and temporal quadrants of the horizontal meridian and extends it to include the six other quadrants given above. Since wide individual differences in central sensitivity are known to occur, it is logical to expect that even greater differences will be found in the more poorly developed periphery. Differences are also to be expected in the results of the investigation by Ferree and Rand and in the present study because the conditions under which the work was done differed in two important respects. (1) The work of Ferree and Rand was done under daylight illumination, the horizontal component of which was 32 ft.-c.; that of the writer under 7 ft.-c. of illumination obtained from a type C_2 lamp. Both the color and the amount of illumination

[1] As reported by Ferree and Rand, these areas which are totally blind or deficient to one color so far as the positive response is concerned, do not seem to be correspondingly deficient in the after-image or cancelling reactions. In fact, so far as could be told, the after-image and complementary reactions are no different in these areas from those in the immediately adjacent normal portions of the retina. (*J. Exper. Psychol.*, 1917, 2, 296.)

to which the eye was adapted, therefore, were different in the two cases. (2) The visual angle subtended by the stimulus used by Ferree and Rand was 3° 36′; that of the writer 1° 16′.

The threshold values in watts x 10^{-13} are given in Tables 2–9, and are shown in the form of curves in Figs. 4–7. In order to represent the entire range of values from center to periphery on one scale, a comparatively large interval had to be chosen for the ordinate. This caused a reduction of the curves for the different colors in the central and paracentral regions which was sufficient to obscure the relatively small changes in result occurring in these regions. To show these small changes, therefore, the threshold values for the central and paracentral regions have in addition been plotted on a scale magnified 20 times and the resultant curves drawn immediately above the other curves in Figs. 4–7. The scale chosen for the abscissa is the same in both cases.

In Figs. 8 and 9 the threshold values for a given color from center to periphery are represented for each of the eight quadrants investigated. These charts are designed to show the variations of sensitivity to each of the colors which occur at corresponding points from meridian to meridian.

Figs. 10 and 11 give the chromatic sensitivity curves. In these curves sensitivity (reciprocal of the threshold value in watts x 10^{-13}) is plotted along the ordinate and degree of eccentricity along the abscissa.

Except that a greater sensitivity was found in the mid periphery, the results obtained are in many respects similar to those of Ferree and Rand. For example, this more extended investigation verifies the six points stressed in their conclusions, given above, with one exception. That is, while the writer found areas that were insensitive to one color and normally sensitive to the other three, she did not find any area outside of the Mariotte spot that was totally blind to color.

The following points of interest may be noted:

(1) *A wide range of sensitivity is found for all colors in passing from the center to the periphery of the field.* This range varies in the different meridional quadrants. The sen-

sitivity is from 276 to 5,170 times greater at the center than at the periphery for yellow, from 400 to 2,443 times greater for green, from 659 to 3,298 times greater for blue, and from 728 to 4,885 times greater for red.

FIGURES 4–7. Curves showing the energy values of spectrum lights required just to arouse the chromatic sensation from center to periphery in the 180°, 90°, 45°, and 135° meridians, light adaptation.

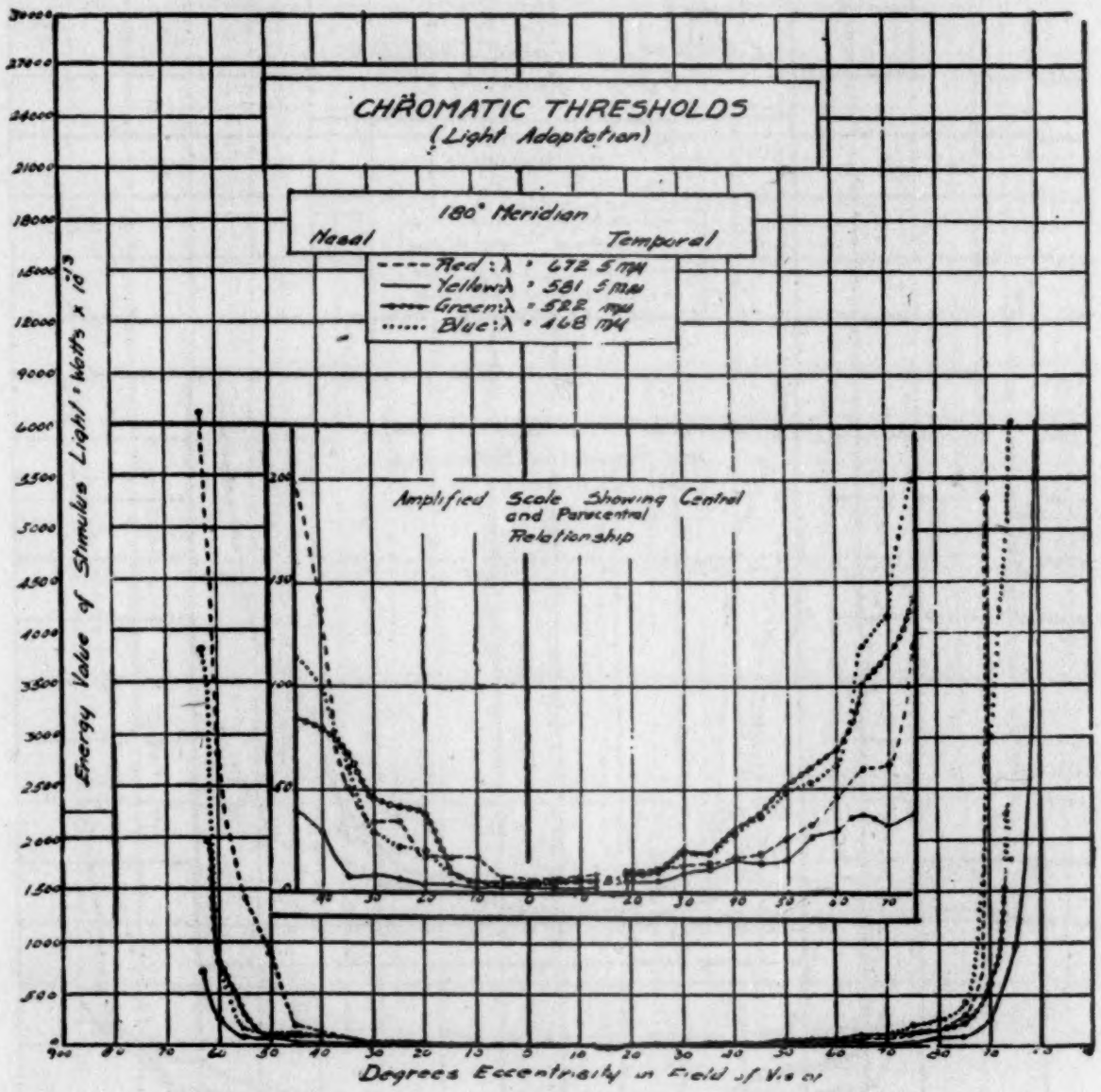

CHROMATIC THRESHOLDS
(Light Adaptation)
180° Meridian
Nasal
Temporal
Red: λ = 672.5 mμ
Yellow: λ = 581.5 mμ
Green: λ = 522 mμ
Blue: λ = 468 mμ
Amplified Scale Showing Central and Parcentral Relationship
Energy Value of Stimulus Light = Watts x 10⁻¹³
Degrees Eccentricity in Field of Vision

FIG. 4

(2) *Great irregularities in sensitivity to a given color are found from point to point in every meridional quadrant.* The greatest irregularity is found in the nasal and upper quadrants. The following striking examples are cited:

(a) the sharp peak in the threshold curve for blue in the lower quadrant between 35° and 45°, the value of the threshold

increasing from 36.17 to 129.53 watts x 10^{-18} between 35° and 40°, then decreasing to 72.56 watts x 10^{-18} at 45°;

(b) the peak in the threshold curve for blue between 40° and 55° in the upper nasal quadrant, the value of the threshold

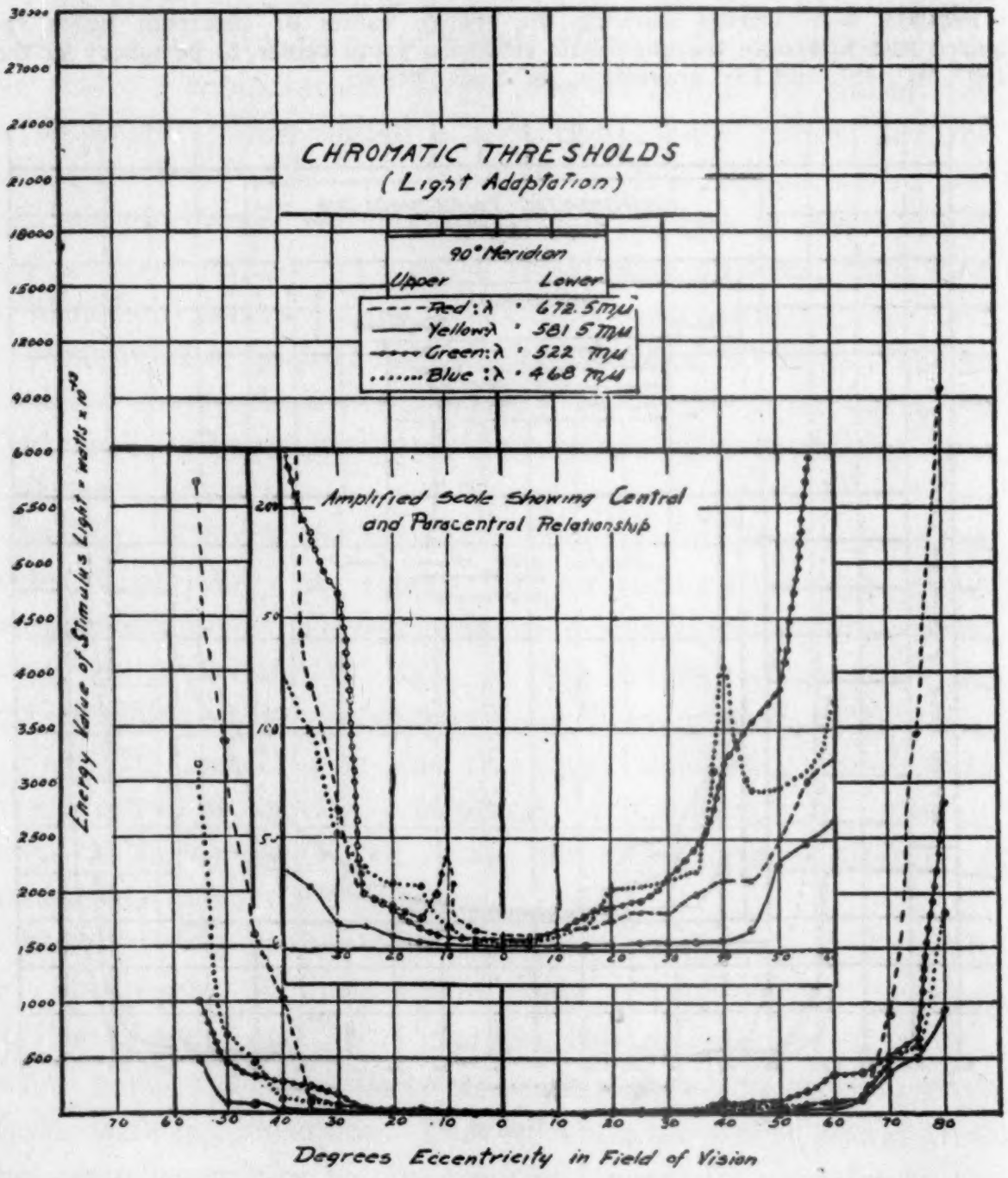

CHROMATIC THRESHOLDS
(Light Adaptation)
90° Meridian
Upper
Lower
Red: λ = 672.5mμ
Yellow: λ = 581.5mμ
Green: λ = 522 mμ
Blue: λ = 468 mμ
Amplified Scale Showing Central and Paracentral Relationship
Energy Value of Stimulus Light = watts x 10⁻¹⁸
Degrees Eccentricity in Field of Vision

FIG. 5

increasing from 98.37 to 916.13 watts x 10^{-18} between 40° and 48°, then decreasing to 348.29 watts x 10^{-18} at 55°;

(c) the peak in the threshold curve for red between 5° and 15° in the upper quadrant, the value of the threshold increasing

from 8.58 to 42.9 watts x 10^{-13} between 5° and 10°, then decreasing to 14.6 watts x 10^{-13} at 15°; and

(d) the smaller humps and peaks in the curve for red at 10° and 25° in the nasal quadrant, in green at 30° and in yellow between 60° and 70° in the temporal quadrant.

(3) *The threshold values increase gradually until near the*

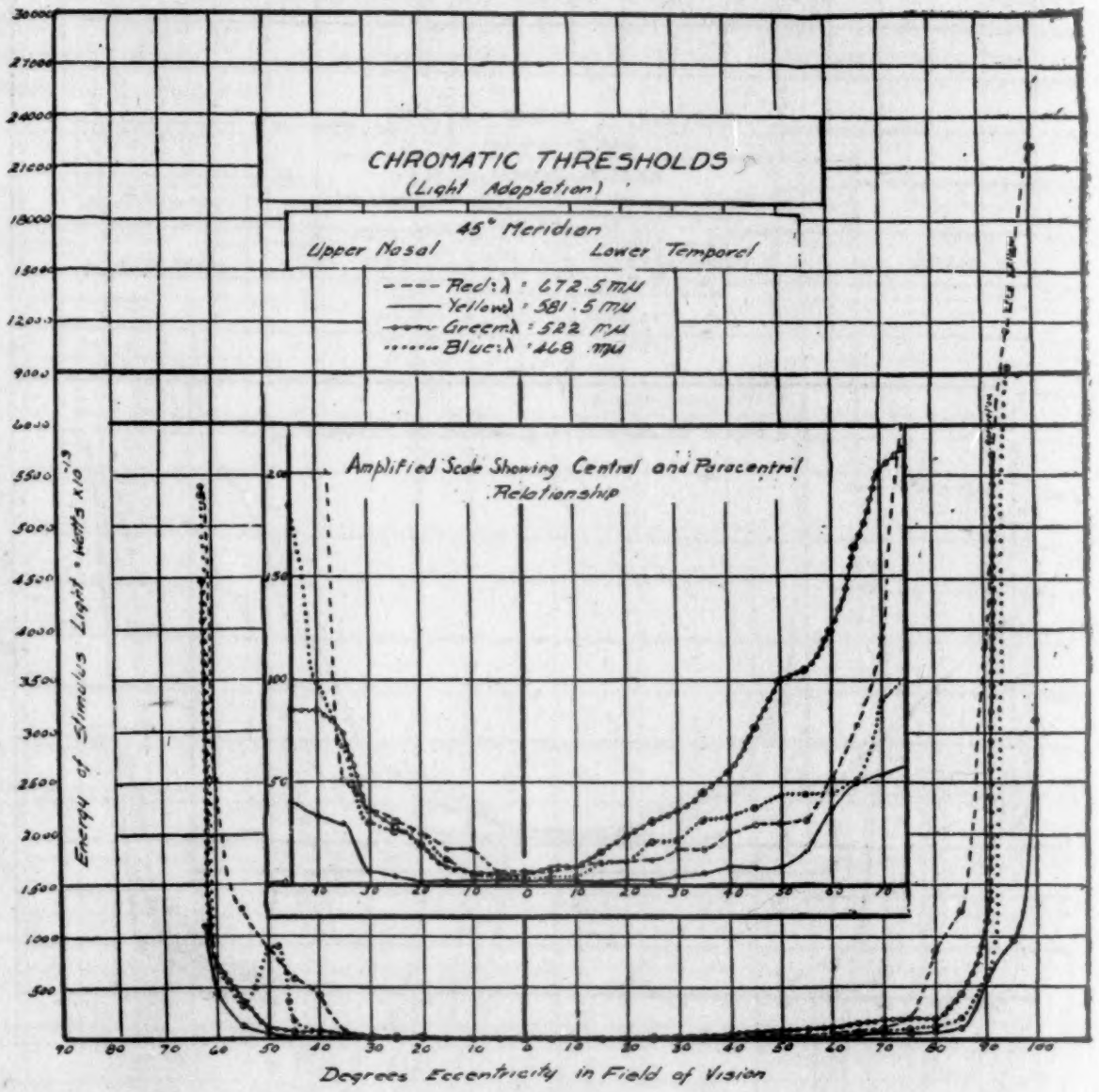

CHROMATIC THRESHOLDS
(Light Adaptation)
45° Meridian
Upper Nasal
Lower Temporal
Red: λ = 672.5 mμ
Yellow: λ = 581.5 mμ
Green: λ = 522 mμ
Blue: λ = 468 mμ
Amplified Scale Showing Central and Paracentral Relationship
Energy of Stimulus Light = Watts x 10⁻¹³
Degrees Eccentricity in Field of Vision

FIG. 6

limits of sensitivity and then very rapidly, as is shown by a sharp bend in the curves of Figs. 4–7. In general, the sensitivity to red falls off the most rapidly from center to periphery, that to yellow the least rapidly. In one quadrant the thresholds for green increase more rapidly than those for red but the reverse is true in all the other quadrants. The sensitivity to yellow is

always noticeably greater than to the other three colors; the curves for red, green and blue, however, crisscross and interlace repeatedly from center to periphery. The amount of increase in the threshold values near the limits of sensitivity is greatest for red, then for blue, green and yellow in the order given.

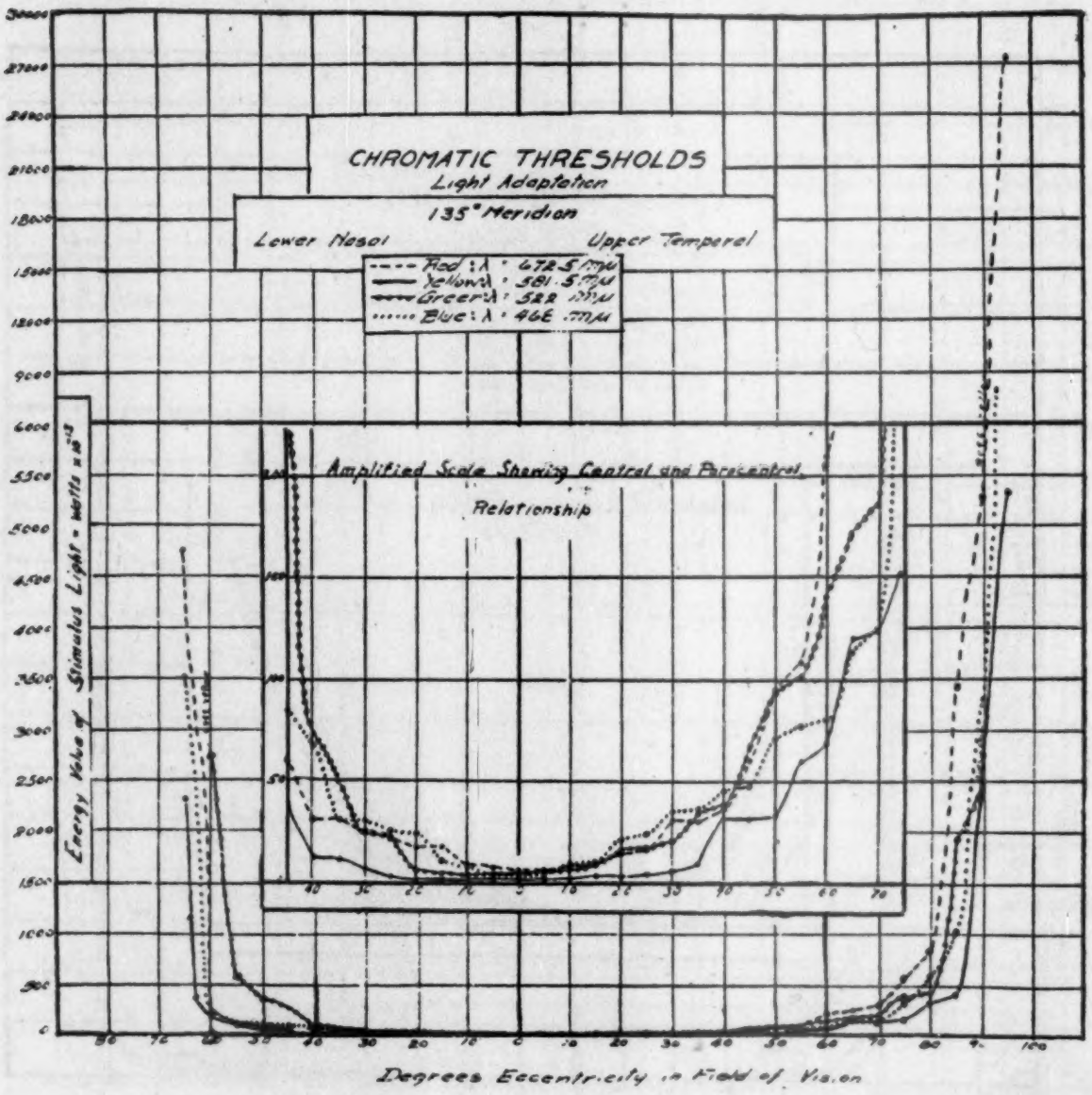

CHROMATIC THRESHOLDS
Light Adaptation
135° Meridian
Lower Nasal
Upper Temporal
Red : λ = 672.5 mμ
Yellow λ = 581.5 mμ
Green λ = 522 mμ
Blue : λ = 466 mμ
Amplified Scale Showing Central and Parcentral Relationship
Energy Value of Stimulus Light - Watts x 10⁻¹³
Degrees Eccentricity in Field of Vision

FIG. 7

This increase for yellow is small as compared with that for the other colors.

(4) *A great difference in rate of change of sensitivity to a given color and to the different colors is found at corresponding points in the various meridional quadrants.* These differences can readily be seen by an inspection of the threshold curves of

Figs. 8 and 9. For example, the sensitivity to green decreases much more rapidly in the temporal, lower temporal and upper temporal quadrants than in the nasal half of the field. That to red, on the other hand, tends to decrease more rapidly in the nasal, upper nasal and lower quadrants. The sensitivity to blue

FIGURES 8–9. Curves showing the energy values for each of the spectrum lights required just to arouse the chromatic sensation from center to periphery of the field at corresponding points in the eight quadrants investigated, light adaptation.

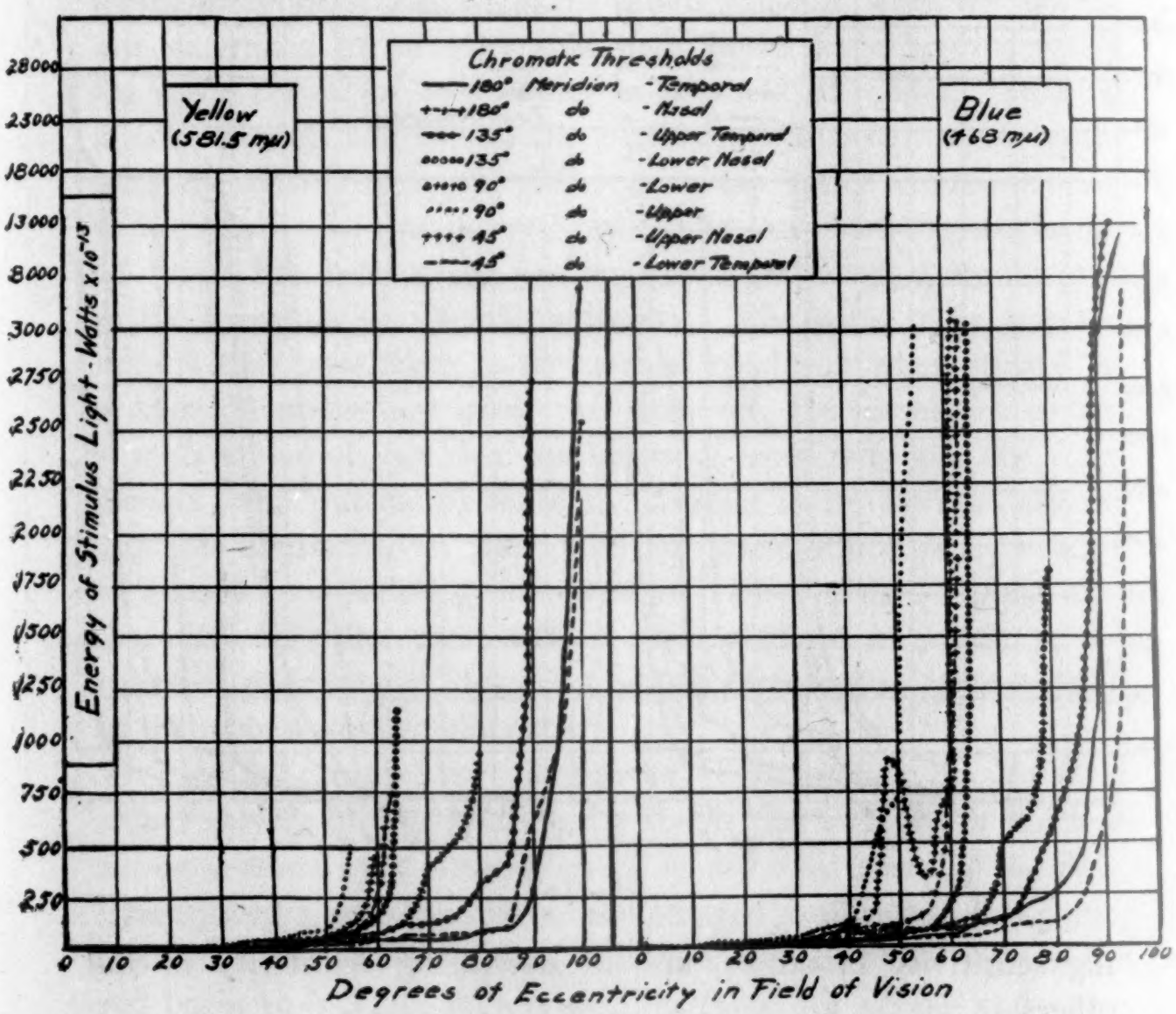


FIG. 8

falls off at about the same rate in all quadrants while that for yellow decreases at very different rates in the different quadrants. In the temporal quadrant, for example, there is little change in the threshold values for yellow from the center to 10°; in the

lower nasal quadrant, little change from the center to 20°; and in the nasal and upper temporal quadrants there is an immediate decrease from the center but at different rates in the two cases. At the same distances from the center of the field, small stretches of equal sensitivity to this color occur in one quadrant, of increas-

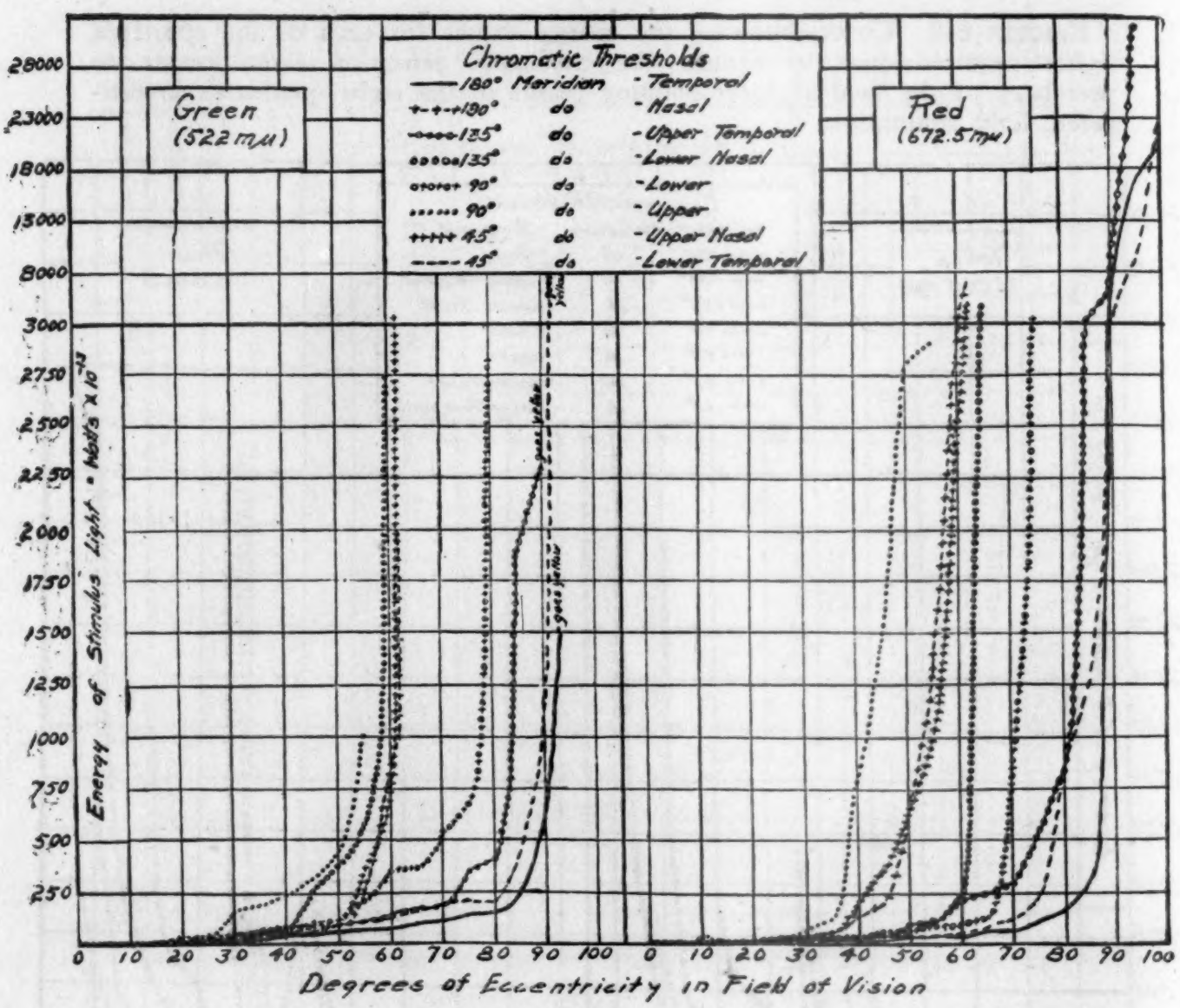


FIG. 9

ing sensitivity in others, and of decreasing sensitivity in still others.

The point of sudden decrease in sensitivity which always occurs near the limits of vision also varies for the different colors and from quadrant to quadrant, as is shown in Figs. 8 and 9. The approximate point at which this occurs for each color in the different quadrants is as follows:

Meridional Quadrant	Degrees Eccentricity in Field of Vision			
	Red	Blue	Green	Yellow
Upper	35	40	50	50
Upper Nasal	35	50	50	50
Nasal	45	55	55	60
Lower Nasal	60	60	40	60
Lower	65	65	50	65
Lower Temporal	75	80–85	80–85	80–85
Upper Temporal	70–80	70–80	80	85
Temporal	85	85	85	90

These results have an important bearing on the relationship of the limits of sensitivity to the different colors when the stimuli are so graded in intensity that their limits have approximately the same degree of eccentricity in the field of vision. That is, a crisscrossing and interlacing of limits will occur as the comparative sensitivity to the different colors varies from meridian to meridian. As was pointed out in the introduction, interlacing of limits has been given an important pathological significance in the literature on clinical perimetry. The point to be stressed here is that interlacing is the normal condition when stimuli of certain intensities are used. If, however, the intensities of the stimuli are so chosen that the limits of sensitivity for one color always occur outside of those for another in the normal subject, then an interlacing of the limits for these stimuli may readily be caused by a pathological condition. Interlacing of limits may therefore be either the result of the conditions of work, or the result of pathology. This point will be discussed in greater detail in the next section of the paper.

(5) *The comparative changes in sensitivity to the different colors sustain a close relationship to the hue changes in the sensation aroused by a given stimulus in different parts of the field.* The following examples have been selected to illustrate this point:

(a) In the upper vertical quadrant the threshold values for red begin to increase rapidly at 35°; those for yellow and green at 50°. At the point of relative decrease in sensitivity to red as compared with that to yellow, the red stimulus is seen as yellow-orange. Green on the other hand, the sensitivity to which remains relatively the same as that to yellow in this region, does not change in hue.

(b) In the upper nasal quadrant also the threshold curve for red shows a relatively greater increase at 35° than the curves for the other colors. Here, too, an increase is noted in the yellow component of the sensation aroused by the red stimulus. At 15° in this quadrant the green shows a distinct change in hue

FIGURES 10–11. Curves showing the chromatic sensitivity of the eye to spectrum lights from center to periphery in the 180°, 90°, 45°, and 135° meridians, light adaptation.

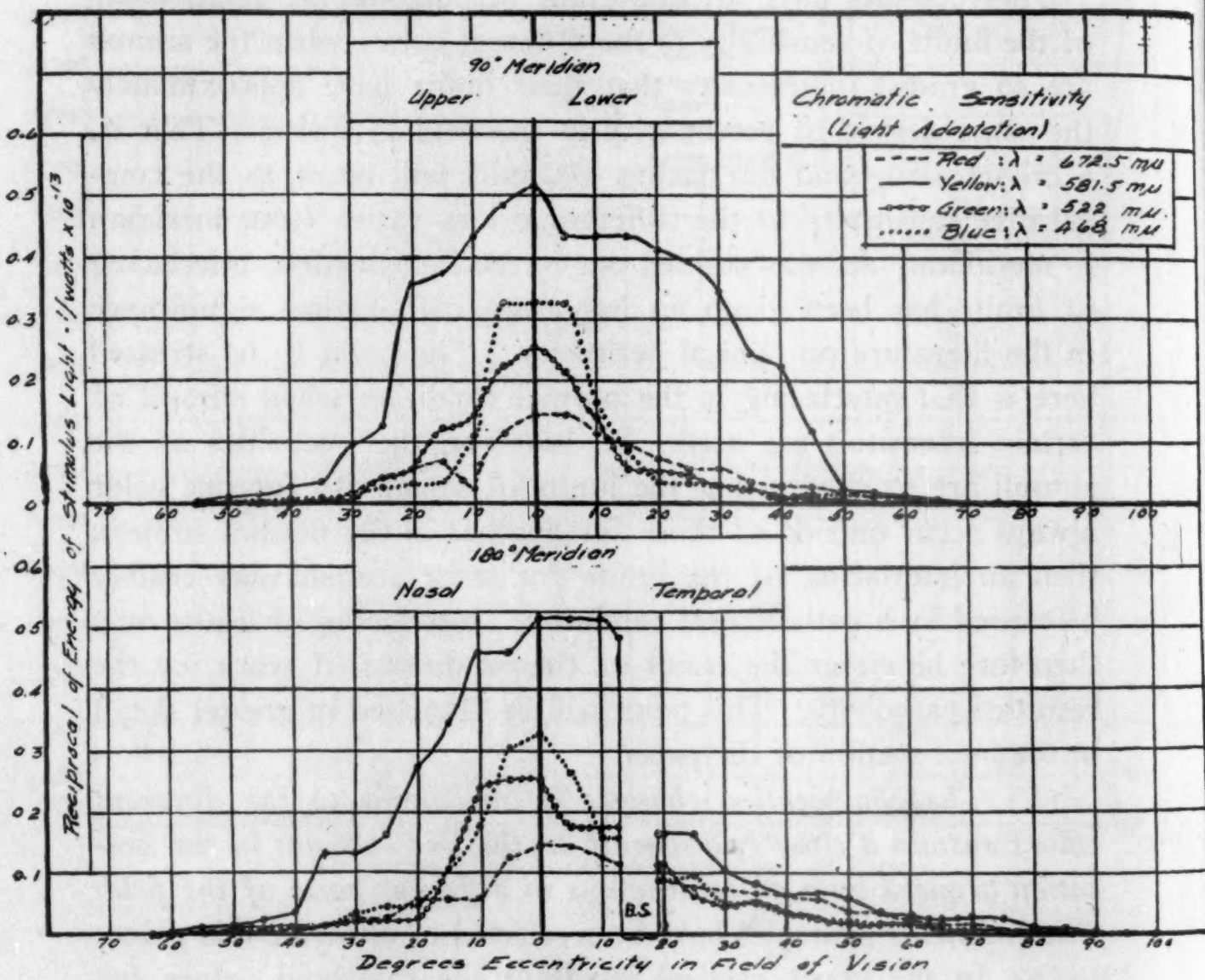


FIG. 10

in the direction of yellow. Examination of the curves shows this to be a point at which sensitivity to green begins to decrease as compared with that to yellow.

(c) Also in the lower quadrant where the threshold values for green increase more rapidly than for the other colors, the green stimulus is seen as a yellow-green.

(d) In the lower temporal quadrant there are a number of changes in the slopes of the threshold curves for red and yellow as compared with each other. From 25° to 60° the red curve rises more rapidly than the yellow. In this region the red stimulus is seen as orange and orange-yellow. At 60° and 65° the slopes and heights of the two curves are more nearly the same. Here the red stimulus is seen again as red. Beyond these points

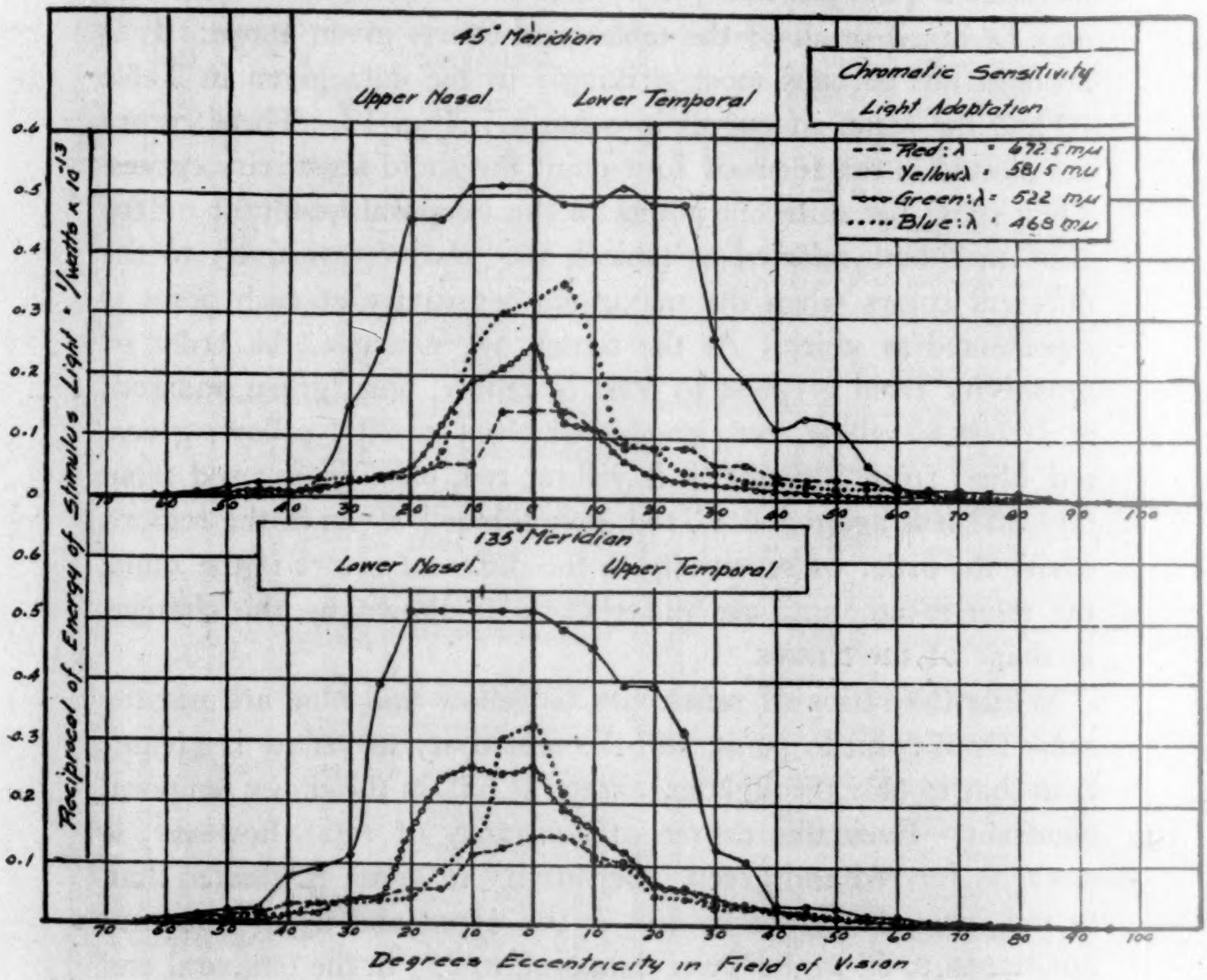


FIG. 11

the red curve rises again much more rapidly than the yellow, and the red stimulus is seen once more as orange. The changes in hue noted above and the threshold values at the points of change can be seen in Tables 2–9, and the slopes of the threshold curves in the regions cited, in Figs. 4–7. In general it may be

said that wherever red or green become yellowish in hue, a decrease in sensitivity to these colors as compared with that for yellow is found. Similar coincidences of color-tone changes and changes in relative sensitivities to the colors, in question, have previously been noted by Ferree and Rand.

(6) *The ratio of sensitivity to the pairs of colors, red and green, blue and yellow changes from point to point in a given meridional quadrant and from quadrant to quadrant.* This fact may be noted in all of the tables and charts given above. It is brought out perhaps most strikingly in the data given in Table 10 and the series of curves in column 1, Fig. 12. These curves are plotted in the form of four-point threshold sensitivity curves. They show for different points in the temporal quadrant of the 180° meridian, selected as typical, the relative sensitivity to the different colors when the maximum sensitivity at each point is represented as unity. At the center, for example, the order of sensitivity from greatest to least is yellow, blue, green and red; at 10° it is yellow, red, green and blue; at 20°, yellow, green, red, blue; from 30°–60°, it is yellow, red, blue, green; and from 60°–90° it is again yellow, red, green, blue. Even in the regions where the order of sensitivity to the different colors is the same, the relative amounts are different as is shown by the changes in shape of the curves.

While the ratios of sensitivity to yellow and blue are not the same from point to point, still the sensitivity to yellow is greater than that to blue throughout, except at 65° in the upper temporal quadrant. Even this degree of constancy of ratio, however, is not true for red and green. Sensitivity to green is greater than to red from the center to 20° in the upper and upper temporal quadrants, to 5° in the lower temporal, to 25° in the temporal and nasal, to 15° in the lower, and to 30° in the lower and lower nasal quadrants. A reversal of sensitivity then occurs. Greater sensitivity to red than to green is found from these points to 40° in the upper and nasal quadrants; to 75° in the lower temporal; to 80° in the temporal; to 50° in the upper temporal (except at the 35° point); to 20° in the lower; to 35° in the upper nasal,

TABLE 10.

TABLE 10.

CHROMATIC SENSITIVITY, LIGHT ADAPTATION.

Showing the chromatic sensitivity to the four spectrum lights expressed as the reciprocal of the energy of the stimulus required just to arouse the chromatic sensation at the points selected in the temporal and nasal quadrants of the 180° meridian and the upper and lower quadrants of the 90° meridian. Included also are ratios of sensitivity to the different colors when the maximum sensitivity at each point is taken an unity.

Degrees Eccentricity in Field of Vision	Temporal Quadrant—180° Meridian								Nasal Quadrant—180° Meridian							
	Sensitivity				Ratio				Sensitivity				Ratio			
	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ
0°	0.486	0.283	0.240	0.145	1.00	0.58	0.49	0.30	0.486	0.283	0.240	0.145	1.00	0.58	0.49	0.30
10°	0.517	0.159	0.177	0.129	1.00	0.31	0.34	0.25	0.460	0.177	0.240	0.058	1.00	0.39	0.52	0.13
20°	0.165	0.088	0.114	0.089	1.00	0.53	0.69	0.54	0.275	0.048	0.026	0.058	1.00	0.17	0.10	0.21
30°	0.103	0.050	0.047	0.072	1.00	0.49	0.46	0.70	0.137	0.033	0.022	0.029	1.00	0.24	0.16	0.21
40°	0.063	0.034	0.031	0.061	1.00	0.54	0.49	0.97	0.034	0.010	0.029	0.007	1.00	0.29	0.85	0.21
50°	0.059	0.020	0.019	0.037	1.00	0.34	0.32	0.63	0.014	0.008	0.010	0.001	1.00	0.57	0.71	0.07
60°	0.031	0.016	0.014	0.021	1.00	0.51	0.45	0.68	0.003	0.001	0.001	0.0001	1.00	0.32	0.32	0.02
70°	0.029	0.007	0.008	0.014	1.00	0.24	0.28	0.48	....	....	....	....	....	....	....	....
80°	0.011	0.003	0.006	0.006	1.00	0.27	0.55	0.55	....	....	....	....	....	....	....	....
90°	0.003	0.0003	0.0015	0.0001	1.00	0.08	0.39	0.02	....	....	....	....	....	....	....	....
																....

	Upper Quadrant—90° Meridian								Lower Quadrant—90° Meridian							
	Sensitivity				Ratio				Sensitivity				Ratio			
	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ
0°	0.486	0.283	0.240	0.145	1.00	0.58	0.49	0.30	0.486	0.283	0.240	0.145	1.00	0.58	0.49	0.30
10°	0.434	0.109	0.143	0.023	1.00	0.25	0.33	0.05	0.435	0.164	0.140	0.116	1.00	0.38	0.32	0.27
20°	0.359	0.033	0.055	0.058	1.00	0.09	0.15	0.16	0.413	0.035	0.051	0.072	1.00	0.08	0.12	0.17
30°	0.096	0.018	0.006	0.014	1.00	0.19	0.06	0.15	0.344	0.030	0.030	0.058	1.00	0.08	0.08	0.17
40°	0.029	0.008	0.004	0.0009	1.00	0.27	0.14	0.03	0.223	0.007	0.011	0.030	1.00	0.03	0.05	0.13
50°	0.011	0.001	0.002	0.0002	1.00	0.13	0.19	0.02	0.026	0.013	0.008	0.019	1.00	0.50	0.30	0.73
60°	....	....	....	....	....	....	....	....	0.016	0.008	0.002	0.011	1.00	0.50	0.13	0.69
70°	....	....	....	....	....	....	....	....	0.002	0.002	0.0018	0.0011	1.00	0.77	0.69	0.42

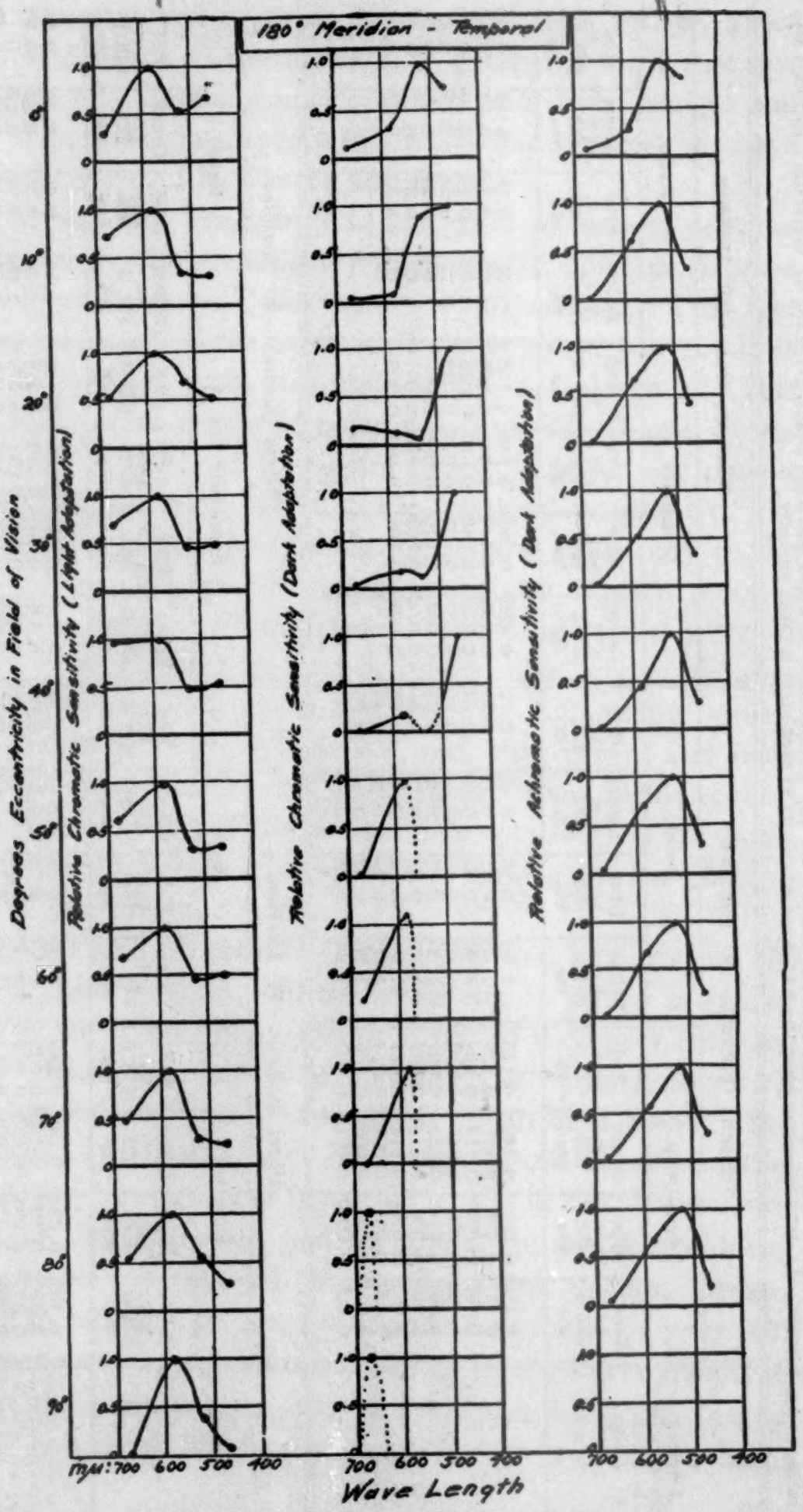


FIGURE 12. Four-point curves for selected points in the temporal quadrant of the 180° meridian showing (a) the relative chromatic sensitivity to the four colors, light adaptation (column 1); (b) the relative chromatic sensitivity to the four colors, dark adaptation (column 2); (c) the relative achromatic sensitivity to the four colors, dark adaptation (column 3). In plotting these curves the highest sensitivity at each point was taken as unity.

and to the limit of vision in the lower nasal quadrant (except at 25° and 30° where the sensitivity is approximately equal to red and green). At the points noted in the different quadrants, a second reversal occurs, the sensitivity again becoming greater to green than to red. This relationship holds to the limit of vision for all quadrants except the temporal and lower temporal where sensitivity to red is once more greater than to green from 92° and 93° respectively to the limit of the field of vision.

Ferree and Rand obtained reversals of sensitivity to blue and yellow as well as to red and green. They did not, however, find a second reversal of sensitivity to red and green such as is noted above. It is obvious from reversals of sensitivity of this kind and from the variations in ratio of sensitivity shown in the tables and charts that there is no evidence for the claim that a constancy of ratio of sensitivity exists between the complementary colors from the center to the periphery of the retina. It will be remembered that Bull and his followers made this claim on the basis of coextensive limits for the pairs of colors equated in cancelling power and in brightness. The fallacy of their method of working has already been pointed out. Hess, Hegg, and Baird have also claimed that it is possible to obtain stable colors, *i.e.*, colors which show no changes in hue from center to periphery. This we have never been able to do, nor is it to be expected when one considers the changing ratio of sensitivity to the different colors from point to point in a given meridional quadrant and from quadrant to quadrant, and the corresponding changes in color-tone which take place.

2. *Effect of Intensity of Stimulus on the Limits of Sensitivity.*

An investigation of the limits of sensitivity may be considered from three points of view:

(a) it may be made a part of the study of the comparative sensitivity of the peripheral retina to the different colors;

(b) it may be considered more specifically in relation to points of theory; and

(c) it may be considered in relation to the practice of perimetry and to diagnosis.

In the first case, the limits should be obtained with stimuli of equal energy. The results will then represent positions in the field of vision for which the retina has the same or nearly the same threshold values for the different colors. In the second case, the problem, considered in relation to its historical development, is twofold: a determination of the relative or apparent limits of sensitivity under the conditions tested; and a determination of the absolute limits.[1] As has already been pointed out, the determination of the apparent limits was given an undue importance in relation to theory by Bull and his followers because of their failure to realize that great irregularity and not uniformity characterizes the decrease of sensitivity from the center to the periphery of the retina. The determination of the absolute limits, however, does sustain an important relation to theory, especially to theories of the paired process type; for if it is found that sensation can be aroused farther out from the center of the retina for one of the paired colors than for the other, this fact must tell against those theories unless some supplementary concept is provided to explain the discrepancy. In the third case, the problem is to select some standard set of conditions and to determine the normal range of variation of size and shape of field and order of ranking as to breadth under the conditions selected.

The determinations made by Ferree and Rand (a) of the limits of sensitivity with stimuli any further increase in the intensity of which tended to decrease rather than to increase the chromatic component of the response, and (b) of the apparent limits for stimuli of lower intensity have been previously mentioned. It will be recalled that these limits were determined in 16 quadrants for red, yellow, green and blue spectrum bands the intensity of which were measured in energy units. The highest intensities were taken from the prismatic spectrum of

[1] By *absolute limits* is meant limits of sensitivity with stimuli any further increase in the intensity of which decreases rather than increases the chromatic component of the response.

a Nernst filament operated at 0.6 amp., and from a spectrum made equal in energy to the blue of this spectrum. Reductions from these intensities were made by means of sectored discs. The following results were obtained:

(1) The far periphery of the retina was found not to be blind to red, blue and yellow. It was merely deficient in sensitivity to these colors. Such extensive fields could not be obtained, however, for green, whatever the intensity of stimulation. The limits for stimuli of lower intensity taken from the prismatic spectrum were widely concentric in the order from greatest to least of red, yellow, blue and green. For stimuli of equal energies of medium intensity they were interlacing.

(2) The amount of change of intensity required to produce a detectable change in the apparent limits in the remote parts of the retina is very great. Because of this fact, Ferree and Rand stress the importance of taking into consideration deviations of 1° to 3° from coincidence of limits when conclusions are to be drawn with regard to comparative sensitivities. Furthermore, the amount of change required to produce a detectable narrowing of the limits varies irregularly from center to periphery in a given meridian and from meridian to meridian, as might be expected from the great irregularity in distribution of sensitivity to the different colors in the peripheral retina. As a result of this irregularity two phenomena are mentioned:

(a) the shape of the zone of sensitivity to a given color changes with the intensity of the stimulus employed in making the determination; and

(b) when stimuli of equal or the same order of intensity are used the limits for red, yellow and blue are found to interlace or crisscross irregularly rather than to coincide in complementary pairs as was reported by Hess, Hegg and Baird in a more limited investigation of the retina's powers of response. The former phenomenon is the direct corollary of the difference in the rate of decrease of sensitivity to the different colors in passing from the center to the periphery of the retina in the different

meridional quadrants; the latter, to the change in ratio of sensitivity to the different colors from quadrant to quadrant.

(3) A difference in the shape of the field for all colors was found at high and low intensities. As the intensity is decreased the field becomes more elliptical in shape, or narrower in the vertical as compared with the horizontal meridian. This,

TABLE 11.

Showing the area of the color fields for stimuli equalized in energy at different levels of intensity. In computing the area, the fields were drawn to a scale of 1 mm. to 1°, and measured with a planimeter.*

Intensity of stimulus (watts x 10^{-13})	Area of fields (sq. cm.)			
	Red	Yellow	Green	Blue
12.5	9.5	43.0	8.3	9.2
25.	27.8	56.6	20.3	19.8
50.	58.0	91.8	39.7	46.9
100.	79.0	121.7	65.9	84.1
200.	93.9	136.4	99.3	114.2
400.	107.5	148.7	121.9	132.7
800.	118.7	155.6	144.1	146.7
1600.	136.9	168.9	155.8	157.7

*For the intensity of stimulus giving the widest possible limits, the areas of the fields in sq. cm. for red, yellow, green and blue are respectively 168.4, 174.6, 163.2 and 170.

it was suggested, is due to a relatively rapid decrease in sensitivity in the vertical and oblique as compared with the horizontal quadrants.

From the threshold curves obtained in the present study for red, yellow, green and blue spectrum lights in eight quadrants, it is possible to determine directly the absolute limits of sensitivity to these colors and by interpolation the apparent limits for any given level of intensity. Interpolation was considered justifiable in this case in view of the closeness of the points at which the threshold values were determined. The apparent limits were determined by passing horizontal planes parallel to the x-axis of the threshold charts at different energy levels. The point of intersection of a given plane and a threshold curve determined the limit for that intensity beyond which the stimulus

in question could not be sensed with any trace of its true hue.

The results of these determinations are given in Tables 11–13 and Figs. 13–25. Figs. 13–25 show the limits of sensitivity to the four colors at nine intensity levels:—12.5, 25, 50, 100, 200, 400, 800, 1,600 watts x 10^{-13} and that intensity which gave the widest possible limits for a stimulus subtending a visual angle of 1°. In Figs. 13–16 are shown the limits for a given color

TABLE 12

Showing a comparison of area of the color fields for stimuli equalized in energy at different levels of intensity and the percentage decrease in area for a given reduction in intensity of stimulus. The areas of the fields for stimuli of 1600 watts x 10^{-13}, are taken as 100.

Intensity of stimulus (watts x 10^{-13})	Comparative areas of field				Intensity of stimulus	Percentage decrease in area of field			
	Red	Yellow	Green	Blue		Red	Yellow	Green	Blue
1600	100	100	100	100	....	....	....	....	....
800	86.8	92.2	92.2	93.1	50.00	13.3	7.9	7.5	7.0
400	78.6	88.1	77.8	84.2	75.00	21.5	12.0	21.6	15.8
200	68.8	80.9	63.4	72.5	87.50	31.4	19.2	36.1	27.6
100	57.8	72.1	42.1	53.4	93.75	42.4	27.9	57.4	46.7
50	42.5	54.4	25.3	29.7	96.88	57.6	45.6	74.2	70.2
25	20.3	33.6	12.5	12.6	98.43	81.8	66.6	87.8	87.4
12.5	6.9	25.0	5.3	5.8	99.21	95.2	74.6	94.2	94.3

at the different intensities; and in Figs. 17–25 the limits for the different colors at a given intensity.

In order to have a single index which will represent size of field for comparative purposes, the fields were plotted to a scale of 1 mm. to 1° and measured with a planimeter. These areas in sq. cm. are given in Table 11. Table 12 has been compiled to show the percentage reduction in area of the color fields for a given reduction in intensity of stimulus; and Table 13 to show in the form of ratios the comparative areas of the fields for the four colors at each intensity, the area of the field for yellow being taken as 100 in each case. In Fig. 26 area of field in sq. cm. has been plotted against the logarithm of the intensity of the stimulus light.

In connection with these results the following points may be noted:

(1) *For very high intensities of stimulus, coincidence of limits for red, blue and yellow with those for white light vision was found in all meridional quadrants with the following exceptions:*

(a) Beyond 95° in the temporal and lower temporal quadrants blue was seen as white whatever the intensity employed; and

(b) Red appeared yellow beyond 90° in the upper temporal quadrant. Also the red stimulus appeared so nearly yellow as the temporal and lower temporal limits were approached that only an observer trained in fine color discrimination could have detected the presence of a red component.

TABLE 13.

Showing a comparison of area of the color fields for stimuli equalized in energy at different levels of intensity when the area of the field for yellow is taken as 100.*

Intensity of stimulus (watts x 10^{-13})	Comparative areas of fields			
	Red	Yellow	Green	Blue
12.5	22	100	19	21
25	49	100	36	35
50	63	100	43	51
100	65	100	54	69
200	69	100	73	84
400	72	100	82	89
800	76	100	93	94
1600	81	100	92	93

*For the intensity of stimulus giving the widest possible limits, the comparative areas of the fields are for red, yellow, green and blue respectively 96, 100, 93, and 97.

In comparing these results with those of Ferree and Rand, who had found coincident limits for red, blue, yellow and white light vision in all meridians, the following differences in the two studies should be borne in mind:

(a) The stimulus employed by the writer subtended a visual angle of 1°16′; that used by Ferree and Rand of 3°26′. Ferree and Rand have recently shown that size of stimulus is a powerful determinant of the visibility of color in the peripheral field, com-

parable with intensity in importance. By increasing the size of pigment stimuli of medium intensity, they found that the limits of sensitivity to red and blue could be made almost coextensive with the limits of the field of vision (66).

FIGURES 13–16. Charts showing a comparison of the limits of sensitivity for each color at nine levels of intensity of stimulus: 12.5, 25, 50, 100, 200, 400, 800, 1600 watts x 10^{-13} and that intensity which gave the widest possible limits for a stimulus subtending a visual angle of 1°. This last intensity is for red 27140; for yellow 6784; for green 5232; and for blue 8127, watts x 10^{-13}.

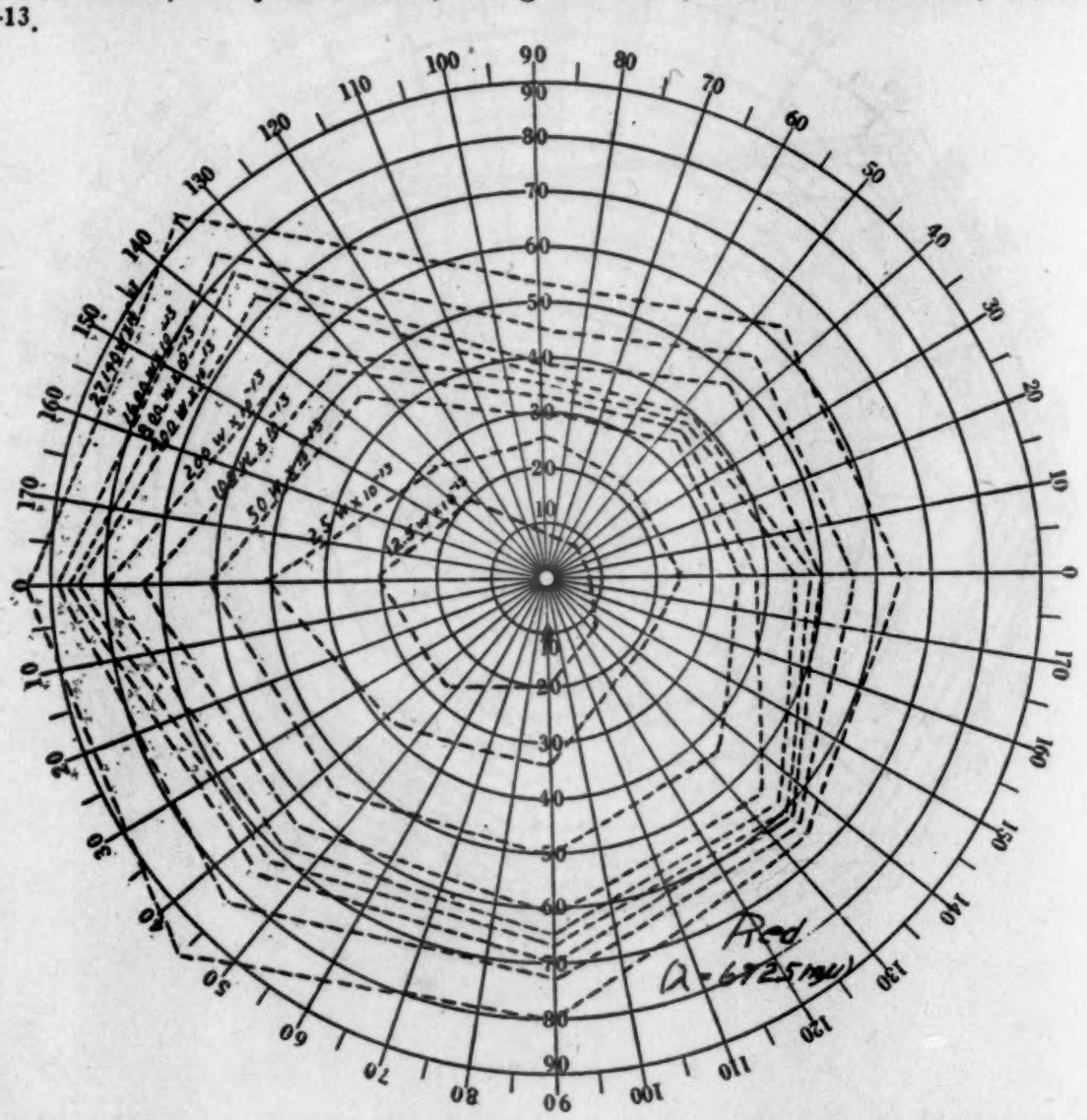


FIG. 13

(b) The limits of white light vision for the writer extend several degrees beyond those obtained by Ferree and Rand, probably because of a difference in curvature of cornea, size of pupil or facial configuration in the observers used. It seems possible,

therefore, that a more remote region of the retina was investigated by the writer than by Ferree and Rand.

(2) *The limits for green fall short of those for the other colors in all quadrants except the nasal, upper nasal and lower; nor could these limits be extended by any increase in intensity.* Ferree and Rand, it will be remembered, found narrower limits

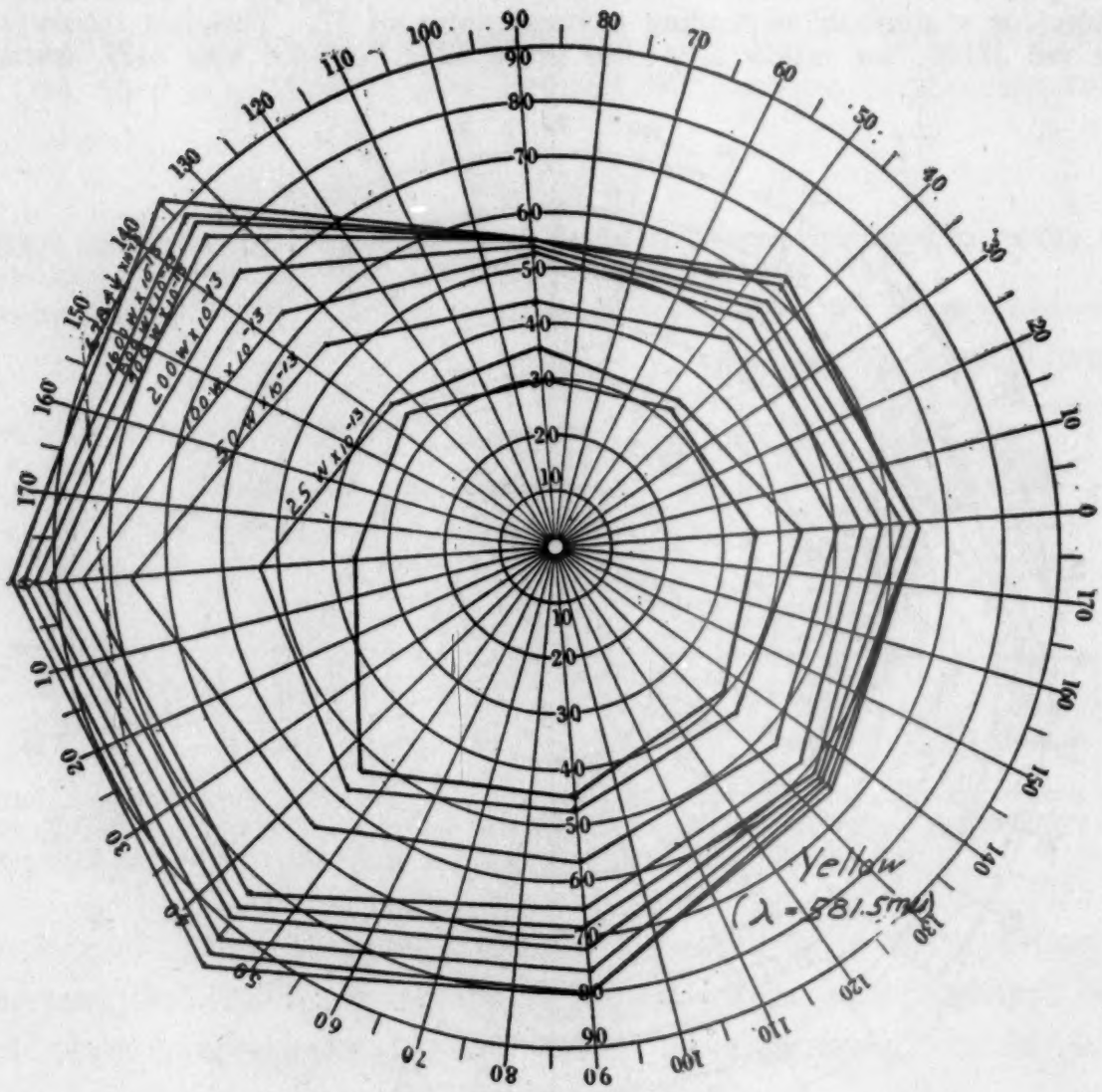


FIG. 14

for green than for the other colors in all meridians. For them the green stimulus was seen as yellow in the far periphery and any increase of intensity of the stimulus increased the yellow component of the sensation aroused.

The main points of difference between our results and those of Ferree and Rand seem to be in the comparative sensitivities to red and green. In our study, as has been indicated above, difficulty

was encountered in determining the thresholds for red near the limits of sensitivity because in approaching the limit there was a gradual change in hue from red to red-orange, then to orange, yellow-orange, orange-yellow and finally yellow. From the mid zone to the periphery of the field the dominant component of the sensation was yellow and the determination of the presence of

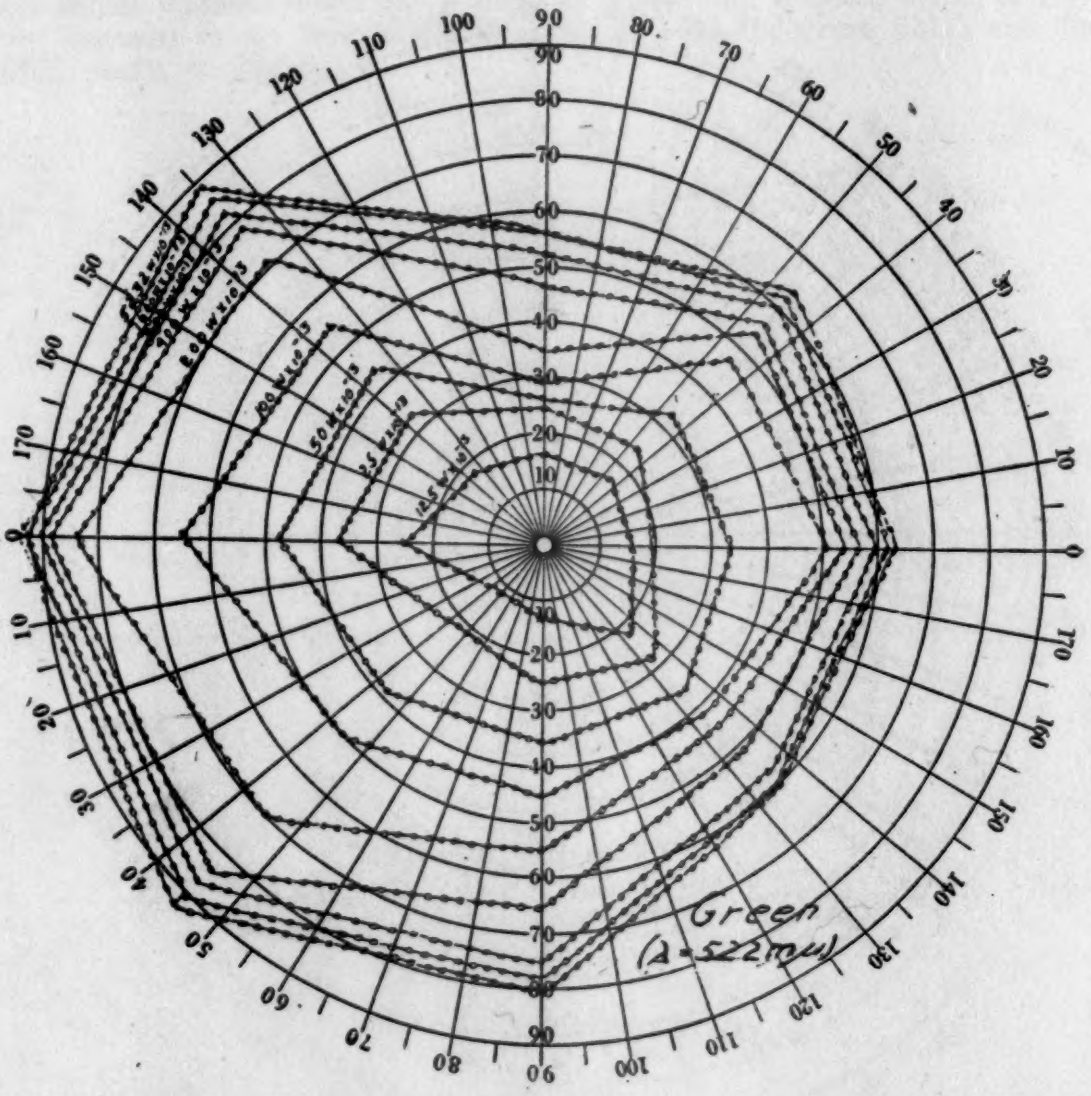


FIG. 15

a red component was therefore increasingly difficult. Ferree and Rand had also found an increase in the yellow component of sensation aroused by the red stimulus in the mid zone of the field, but in the more remote portions of the field the yellow component disappeared and the stimulus was seen as red. Moreover, they did not find a region of greater sensitivity to green than to

red in these remote portions of the field as was found by the writer.

Differences of result of this kind raise the question of individual variations in the relative sensitivity of the peripheral retina to red, green and yellow quite apart from those found in central vision. It was hoped that an investigation of this point could

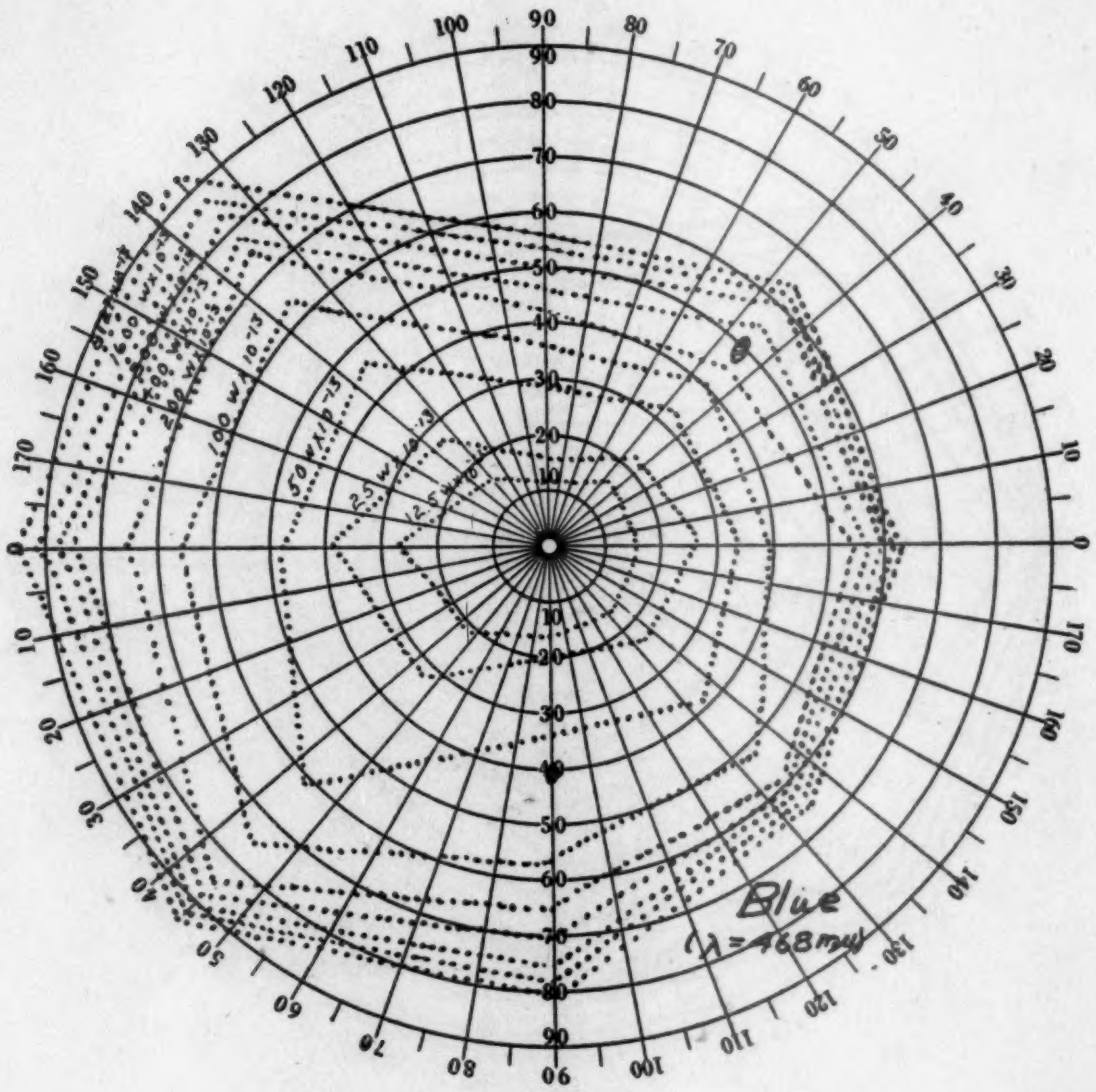


FIG. 16

have been made on a group of observers before the publication of this study. This, however, has not been possible.

(3) *With stimuli equalized in energy at the lower intensities an interlacing of limits was found for blue and red as was obtained by Ferree and Rand.* The results differ, however, in that the latter found much narrower limits for green than for blue and red at all intensities, while the writer finds the limits for

blue, red and green stimuli of equal energy to interlace at every level of intensity. A comparison of the areas of the fields, however, shows that the zone of sensitivity for green is smaller than that for red and blue for the stimulus of highest intensity used

FIGURES 17–25. Charts showing a comparison of the limits of sensitivity for red, yellow, green, and blue at each of the nine levels of intensity: 12.5, 25, 50, 100, 200, 400, 800, 1600 watts x 10^{-13} and that intensity which gave the widest possible limits for a stimulus subtending a visual angle of 1°. This last intensity is for red 27140; for yellow 6784; for green 5232; and for blue 8127, watts x 10^{-13}.

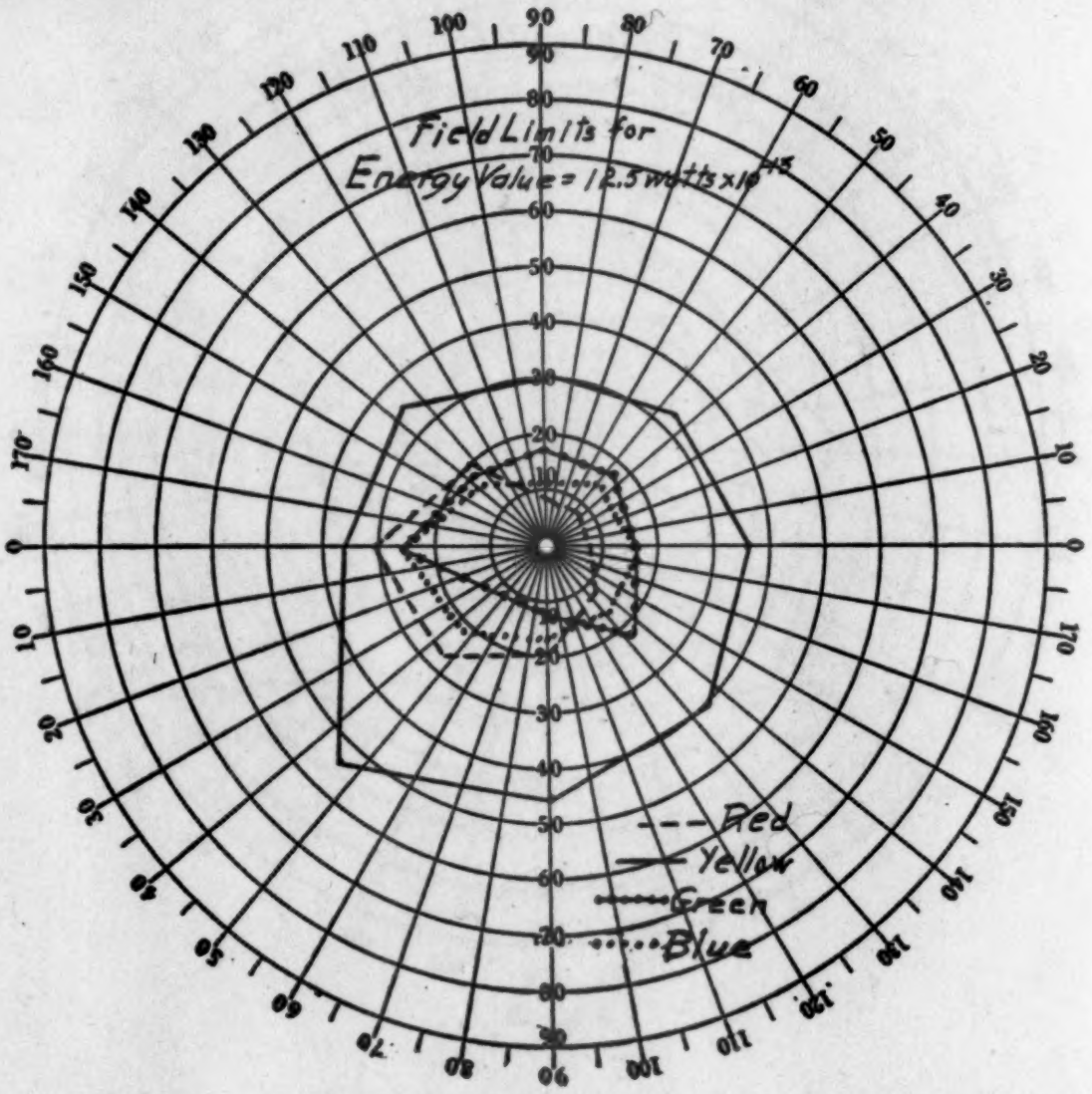


FIG. 17

and for all intensities lower than 200 watts x 10^{-18}. Between 200 and 1600 watts x 10^{-18}, the zone of sensitivity for red, was found to be the smallest.

(4) *The change in intensity required to produce a detectable change in the limits of sensitivity in the more remote parts of*

the retina is very great. This is shown by the sharp rise of the threshold curves near the limits of sensitivity and also by the crowding together of the isopters representing the limits of the fields at different intensity levels, as the absolute limit is approached. Furthermore, this critical change of intensity varies quite irregularly from quadrant to quadrant. These results are

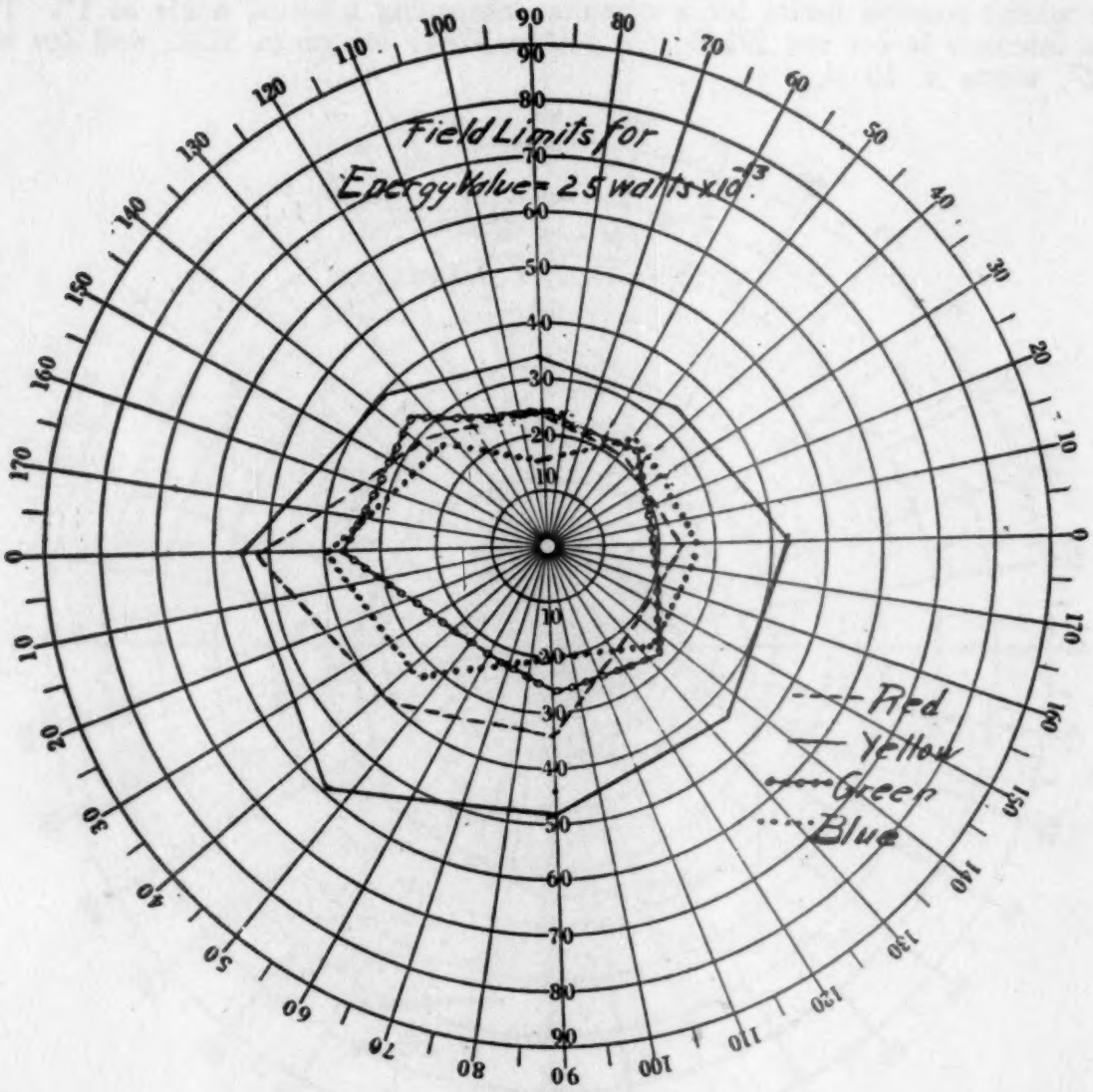


FIG. 18

in complete accord with those obtained by Ferree and Rand in the two quadrants investigated by them.

(5) *A change of shape of the field of sensitivity for a given color occurs with change of intensity of stimulus.* This result is a direct corollary of the irregularity of distribution of sensitivity in the different quadrants. At very high intensities of stimulus the fields are approximately circular in shape; at medium intensi-

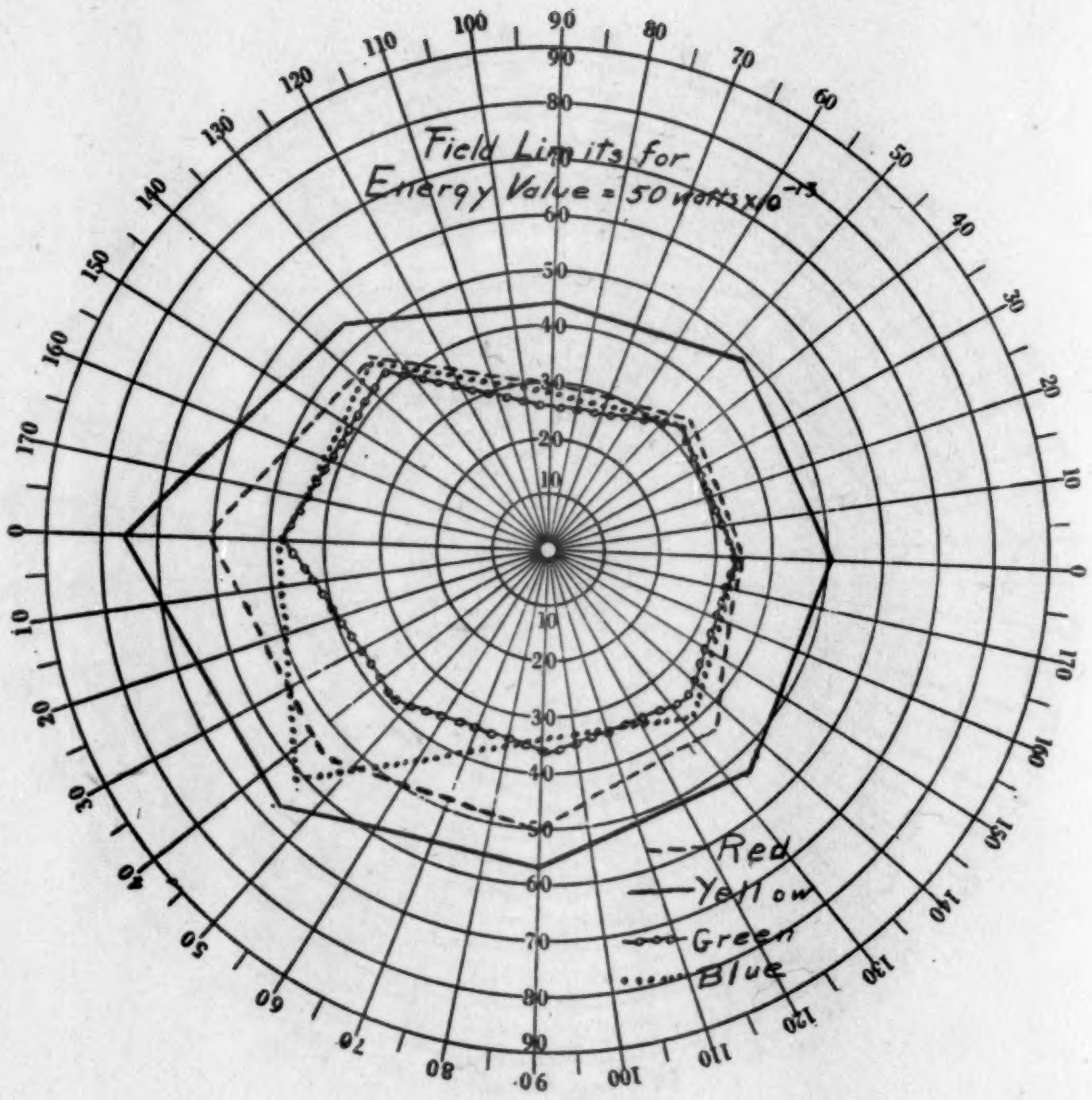

Field Limits for
Energy Value = 50 watts x 10 -13
Red
Yellow
Green
Blue

FIG. 19

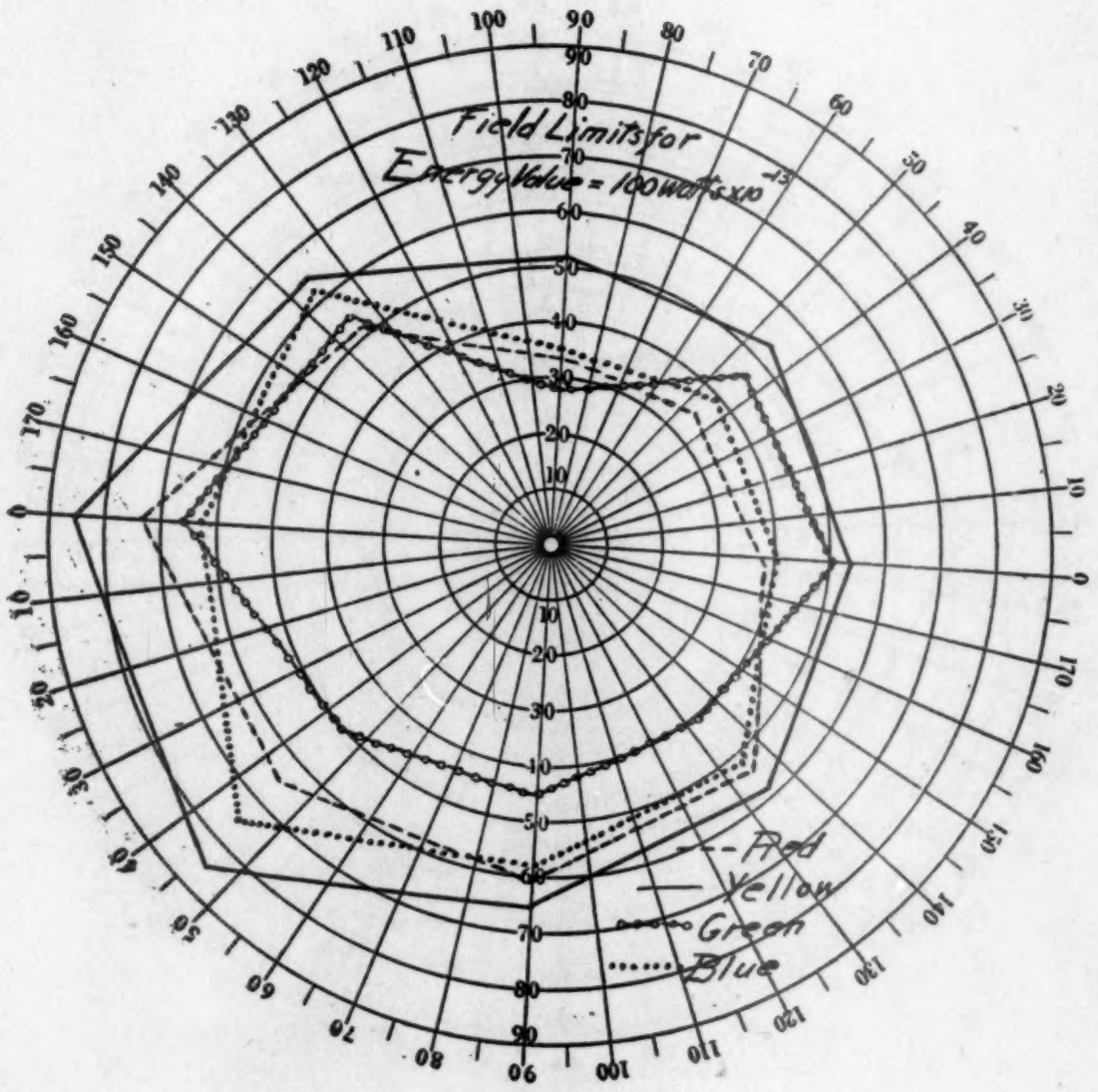

Field Limits for
Energy Value = 100 watts x 10 -13
Red
Yellow
Green
Blue

FIG. 20

ties they tend to become elliptical, or narrower in the vertical and oblique quadrants as compared with the horizontal quadrants; and at very low intensities they tend again to become circular. This is due to the fact that in the horizontal quadrants the limits recede at first slowly, then more rapidly as the intensity of the stimulus is decreased, while in the vertical and oblique quadrants

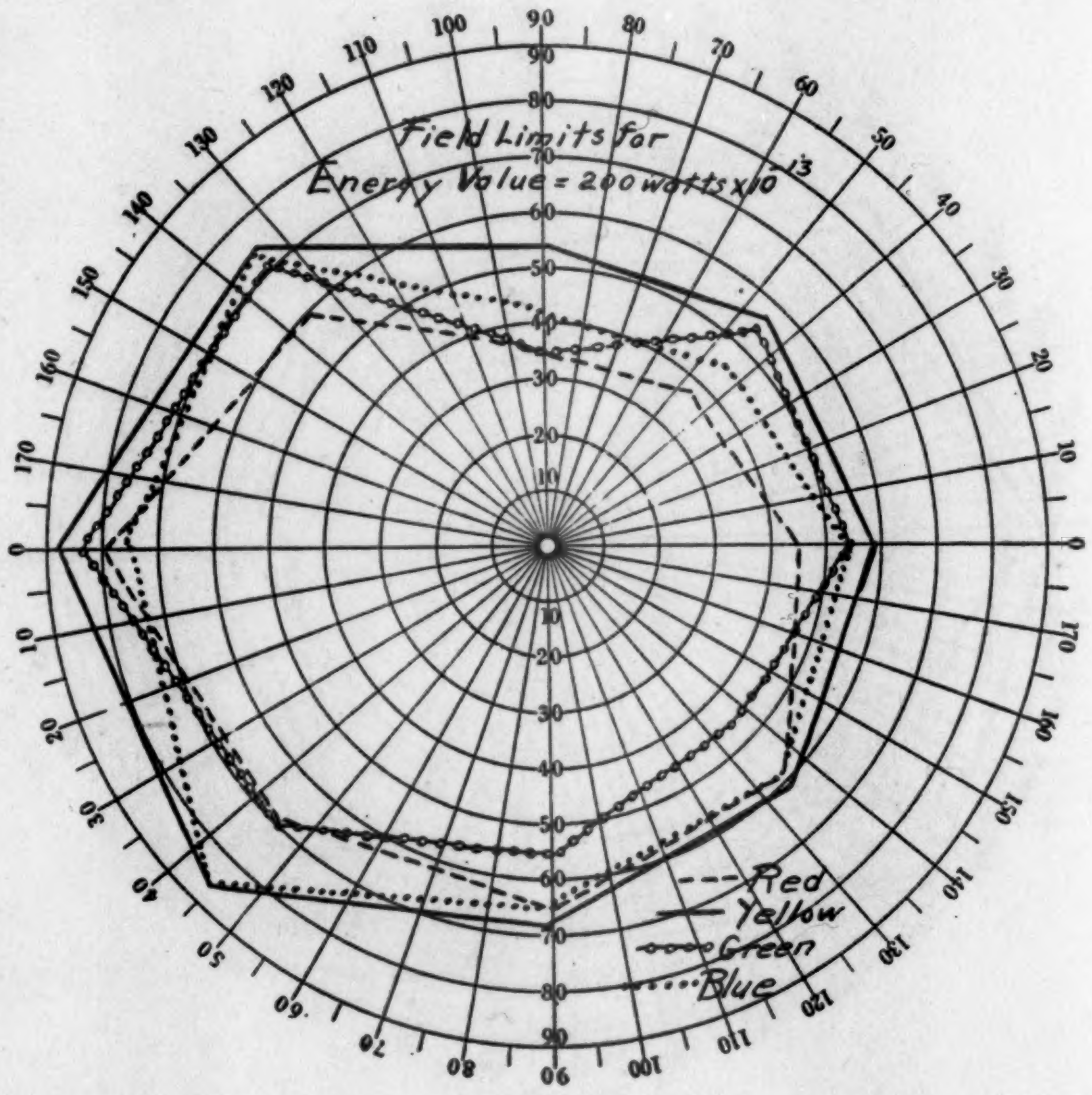


FIG. 21

the recession is more uniform throughout the intensity scale. The sensitivity and threshold curves of Figs. 4–11 offer for the first time direct evidence that different rates of decrease in sensitivity occur in the different quadrants, a fact which had been inferred by Ferree and Rand from the results obtained in two quadrants and from the change of shape of the fields for different intensities.

Interlacing of limits is a second corollary of irregularity of distribution of sensitivity to the different colors in the various quadrants. As has already been stated, interlacing of limits is the general finding when the intensities of the stimuli are approximately the same. Bull, Hess, Hegg, and Baird, it will be remembered, had claimed coincidence of limits for properly selected

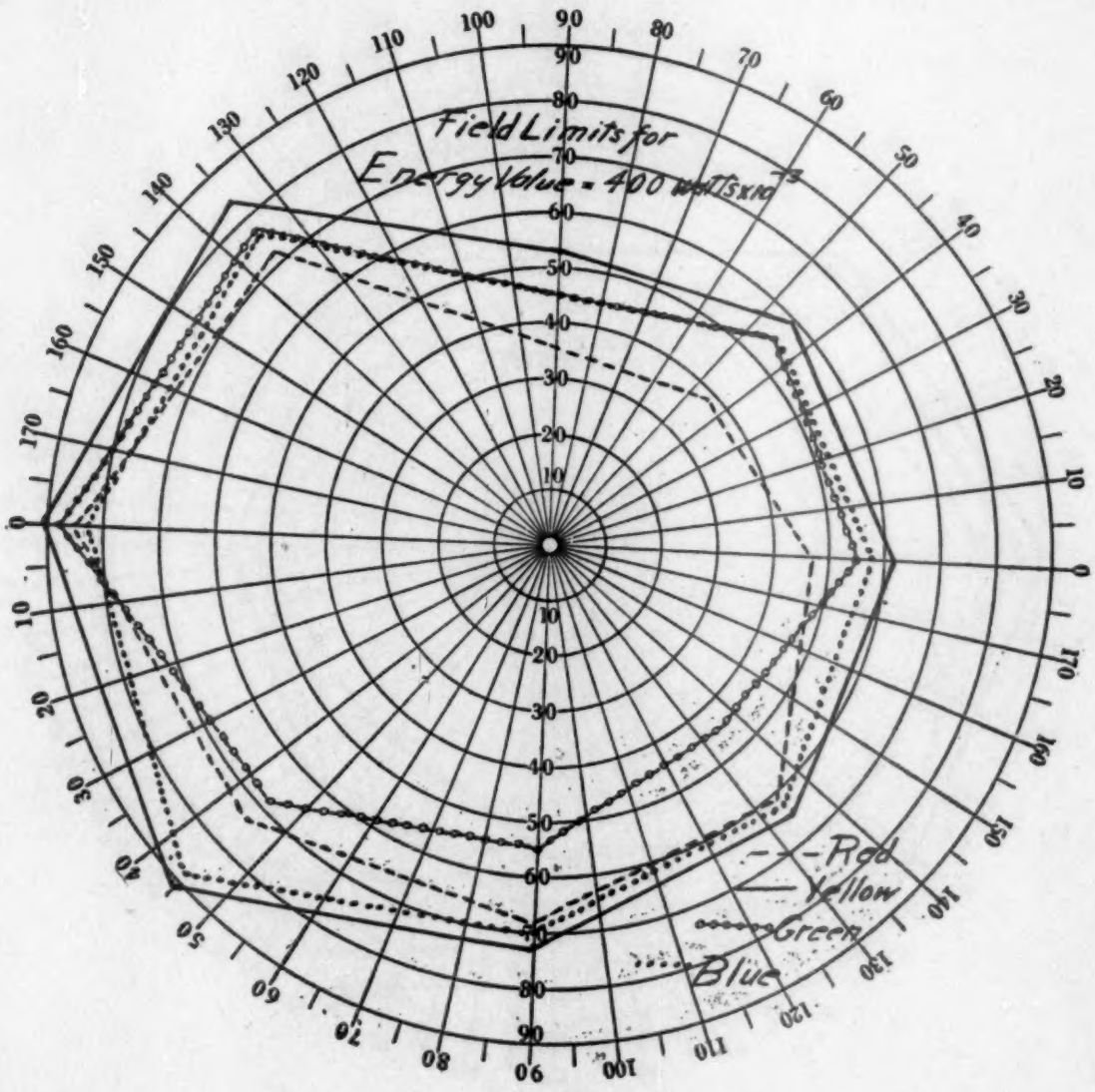


FIG. 22

filter and pigment complementary colors when equalized in brightness and cancelling power for central vision. This general claim was based on an examination of the limits at one level of intensity. The failure of the limits for the pairs of spectrum colors used in these experiments to coincide whatever intensity of stimulus is used, is shown in Figs. 17–25. Also a comparison of the sensitivity curves for these colors in the different meridians

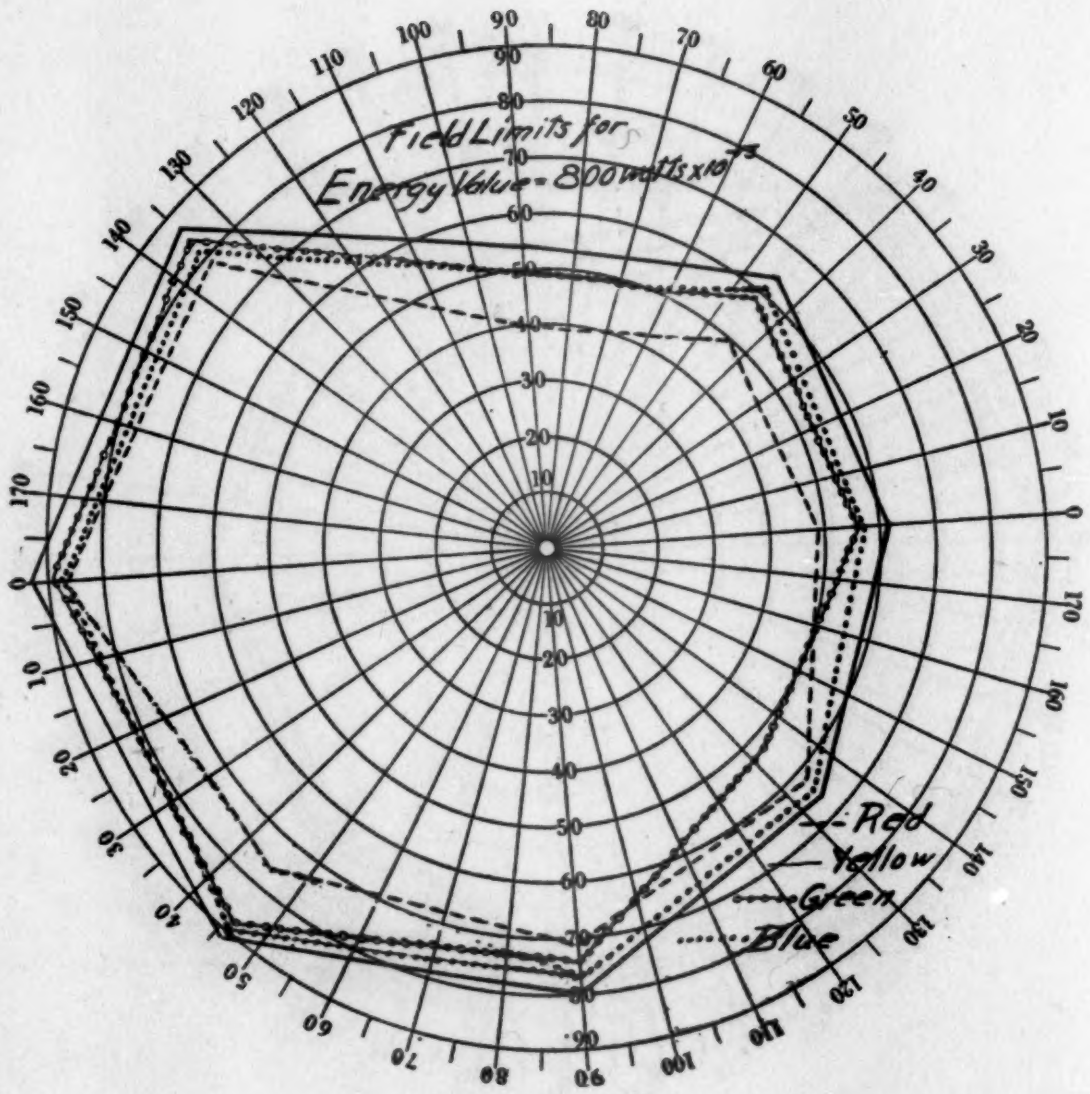

Field Limits for
Energy Value - 800 watts x 10⁻⁷
Red
Yellow
Green
Blue

FIG. 23

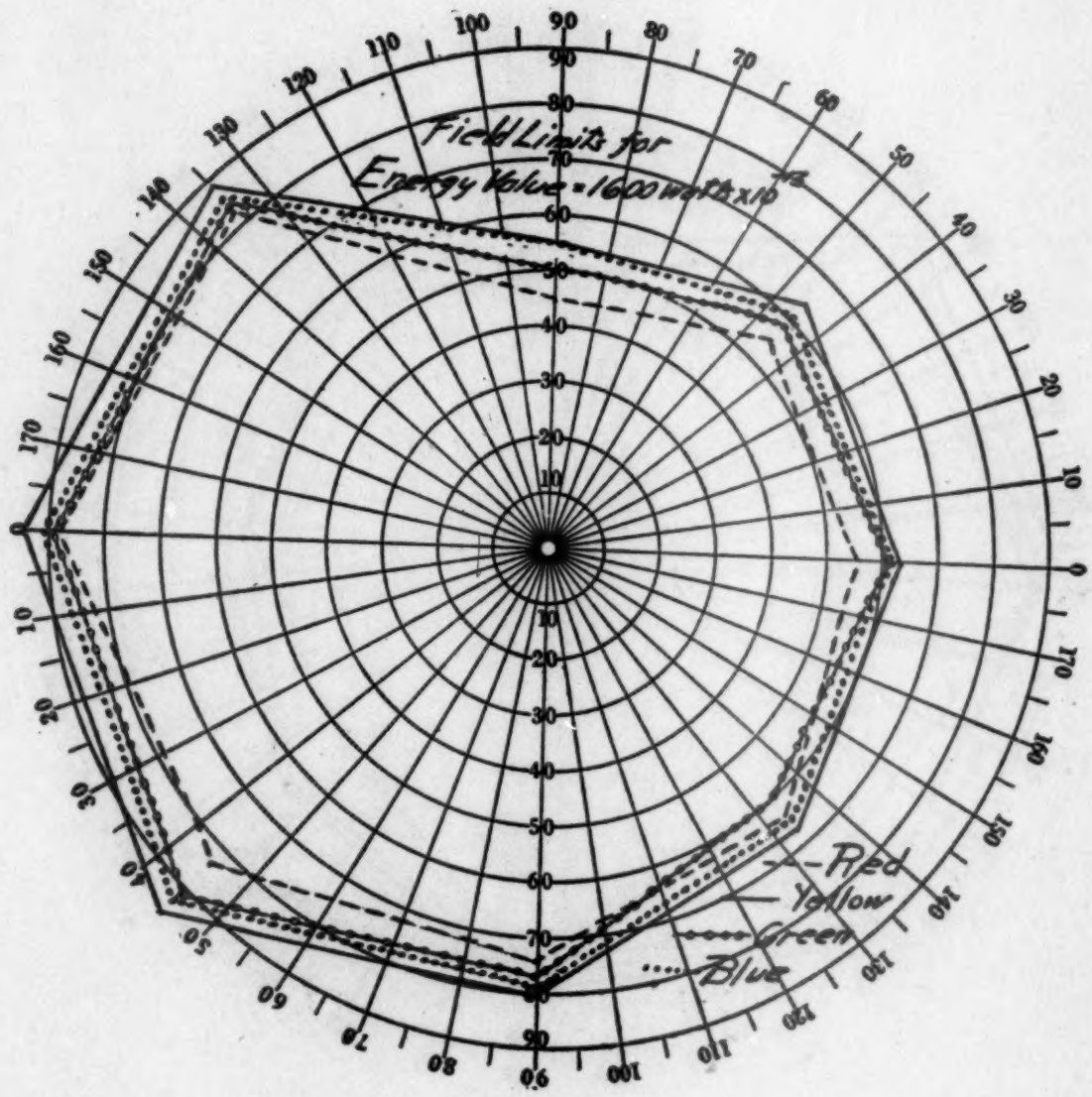

Field Limits for
Energy Value = 1600 watts x 10
Red
Yellow
Green
Blue

FIG. 24

will show that coincidence of limits can not be expected at any level of intensity; nor does it seem possible that any relation of intensities can be chosen that will make them coincide. Because of the changes in the ratios of sensitivity to the different colors from quadrant to quadrant, the limits will inevitably interlace or be irregularly concentric. Coincident or regularly concentric

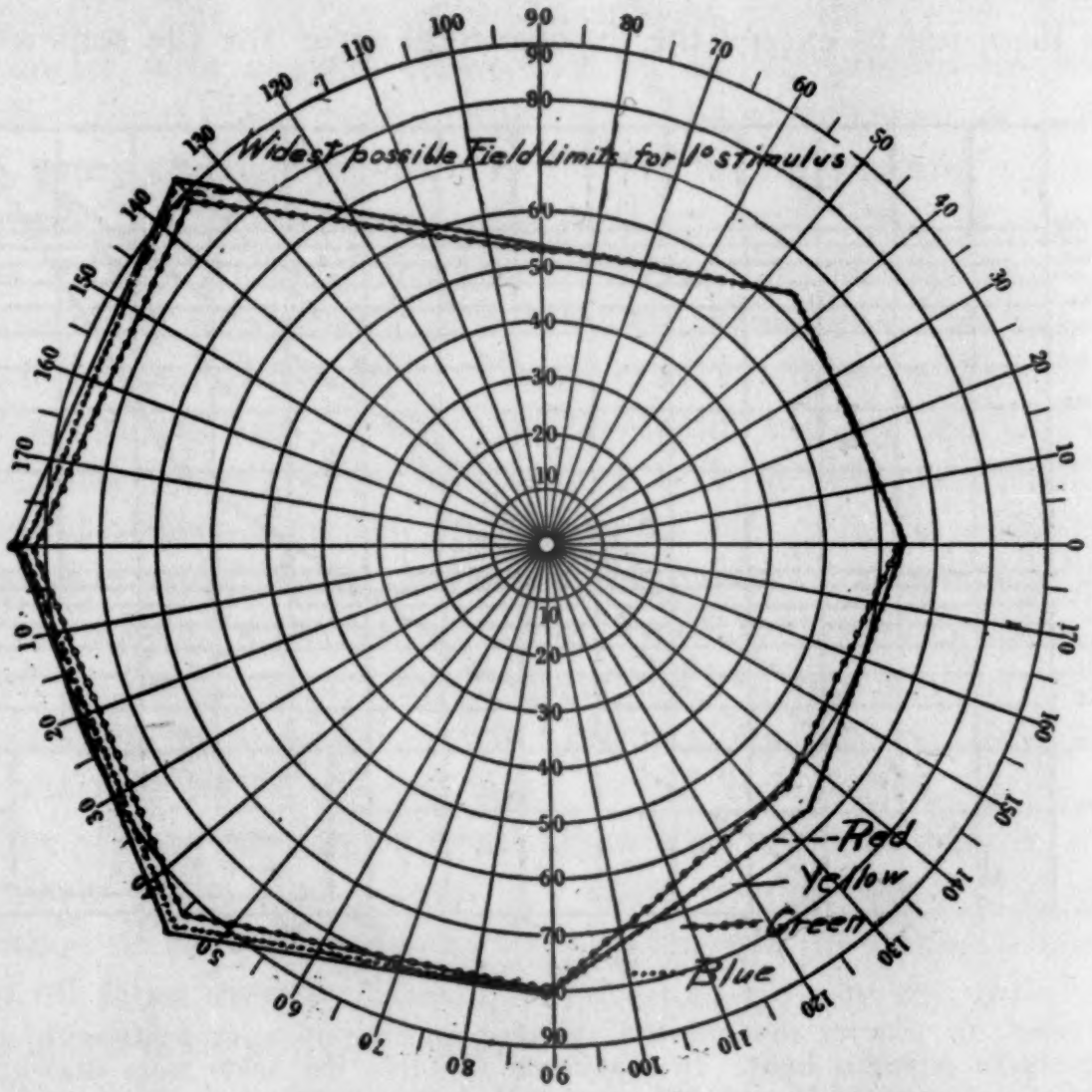


FIG. 25

limits imply a constancy or approximate constancy of ratio of sensitivity for the different colors from quadrant to quadrant. This, as our data on sensitivity show, does not exist. Moreover, an inspection of the maps given in Figs. 17–25, representing the fields at different levels of intensity, shows that the limits for red and green invariably interlace, with wide points of divergence in some quadrants, and that the limits for blue and yellow are very

irregularly concentric. It seems clear then that no one intensity or ratio of intensities of stimulus for the paired colors can be found which will give coincident limits in all quadrants inside the limits of white light vision. Nor, indeed, did Bull, Hess and Baird obtain the coincidence they claimed. Their tables of results show that variations in limits which, according to our data, should be considered as significant, were apparently considered by them not to exceed the experimental error for the somewhat

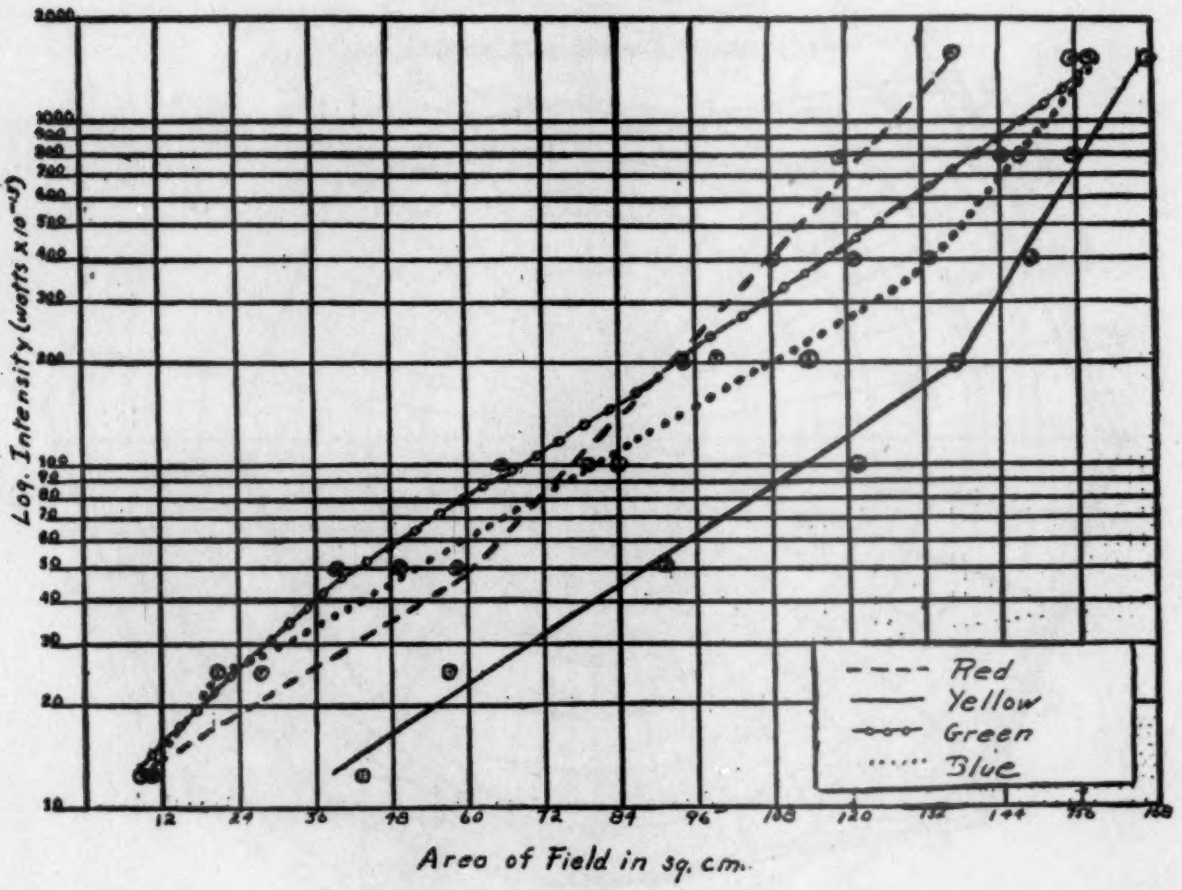


FIGURE 26. Curves showing the variation in area of color fields with log. intensity of stimulus light. In computing the area the fields were drawn to a scale of 1 mm. to 1° and measured with a planimeter.

rough conditions under which they worked. The great changes in sensitivity which occur within 1° or 2° near the limits of the fields obtained by them and the importance of taking these changes into account where points of theory are in question have already been pointed out.

(6) *There is a general tendency for area of field to vary as the logarithm of the intensity of the stimulus light.* This relation-

ship, however, is by no means perfect. The fields for the lowest intensities used are larger and those for the highest intensities smaller than would be the case if a perfect relationship existed between area of field and logarithm intensity of stimulus.

It was thought to be of interest at this point to compare the size of the color fields obtained on a standard perimeter with pigment stimuli and those obtained with spectrum lights of known intensity. The former were determined on the Ferree-Rand perimeter with a strict observance of all the precautions prescribed for the use of this perimeter. The stimuli used were the red, green and blue pigments of the Heidelberg series of colored papers. The illumination on the perimeter arm was 7 ft.-c. and was of approximately daylight quality. The preexposure and surrounding field in case of the colored stimuli were a gray of the brightness of the color. The external conditions under which the comparison of the limits for spectrum and pigment stimuli was made, were, therefore, identical with the exception of the method of presenting the stimulus to the eye. On the perimeter, the eye is held fixed and the stimulus is moved to different points of eccentricity in the field of vision. With the rotary campimeter used for the spectrum stimuli, the stimulus is kept stationary and the eye moves to take eccentric fixation along the graduated arm of the instrument. Fields taken by the two methods differ in shape. They are larger when taken with the campimeter, particularly in the upper, lower and nasal regions, because by this method of presenting the stimulus to the eye the stimulus is not cut off from view by facial configuration, *e.g.*, by the eyebrows, bridge of nose, and cheek bones.

The fields for the pigment stimuli are given in Chart A, Fig. 27. It is seen that, except for the difference in shape of field noted above, they approximate quite closely to the fields for spectrum stimuli having an energy value of 100 watts x 10^{-13} for red and blue and of 50 watts x 10^{-13} for green. The fields for these spectrum stimuli are given for comparison in Chart B, Fig. 27. This comparison affords us a rough subjective evaluation of the energy of the effective chromatic component of the pigment stimuli ordinarily used in clinical perimetry. So evaluated, the green

of the Heidelberg series of papers has an intensity of only one-half that of the red and blue. This is not surprising to anyone

FIGURE 27. Showing the limits of sensitivity for red, green and blue standard pigments as determined with the Ferree-Rand perimeter under 7 foot-candles illumination (chart A); and the limits for red, green, and blue spectrum stimuli which most closely approximate those obtained for the pigment stimuli (chart B). The energy values of the spectrum stimuli giving these limits are 100 watts x 10^{-13} for red and blue, and 50 watts 10^{-13} for green.

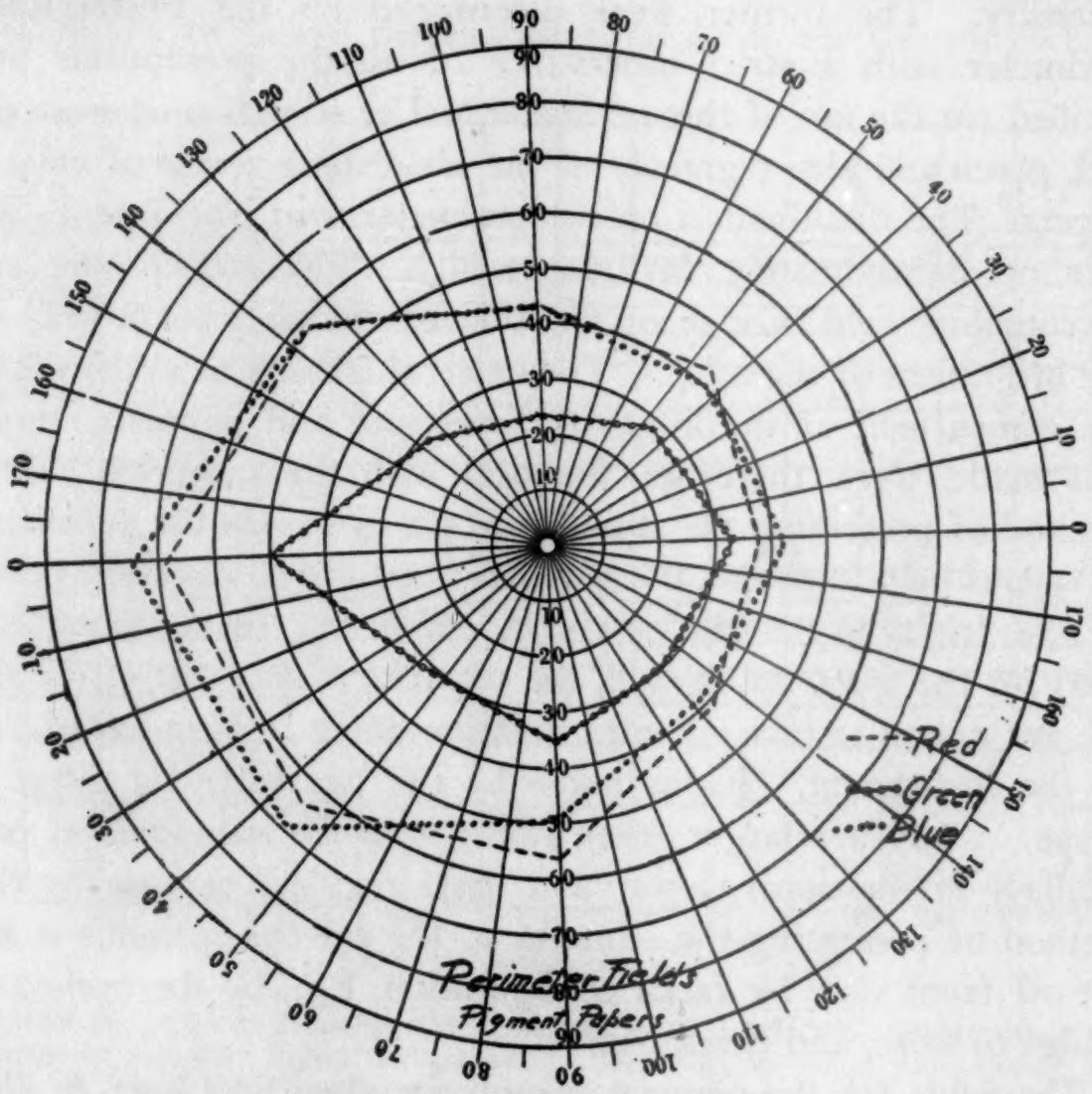


FIG. 27A.

who has used these pigments for perimetric work and has been impressed with the low saturation of the green as compared with the red and blue stimuli.

The foregoing results have a direct bearing on two important misconceptions that have been held by certain clinicians:

(a) the order of ranking of fields as to breadth is blue, red, green, and

(b) an interlacing of the fields or a reversal of this order is indicative of pathological disturbance.

The results obtained both by the writer and by Ferree and Rand show conclusively that size of field depends, among other factors, on the intensity of stimulus employed; and the order

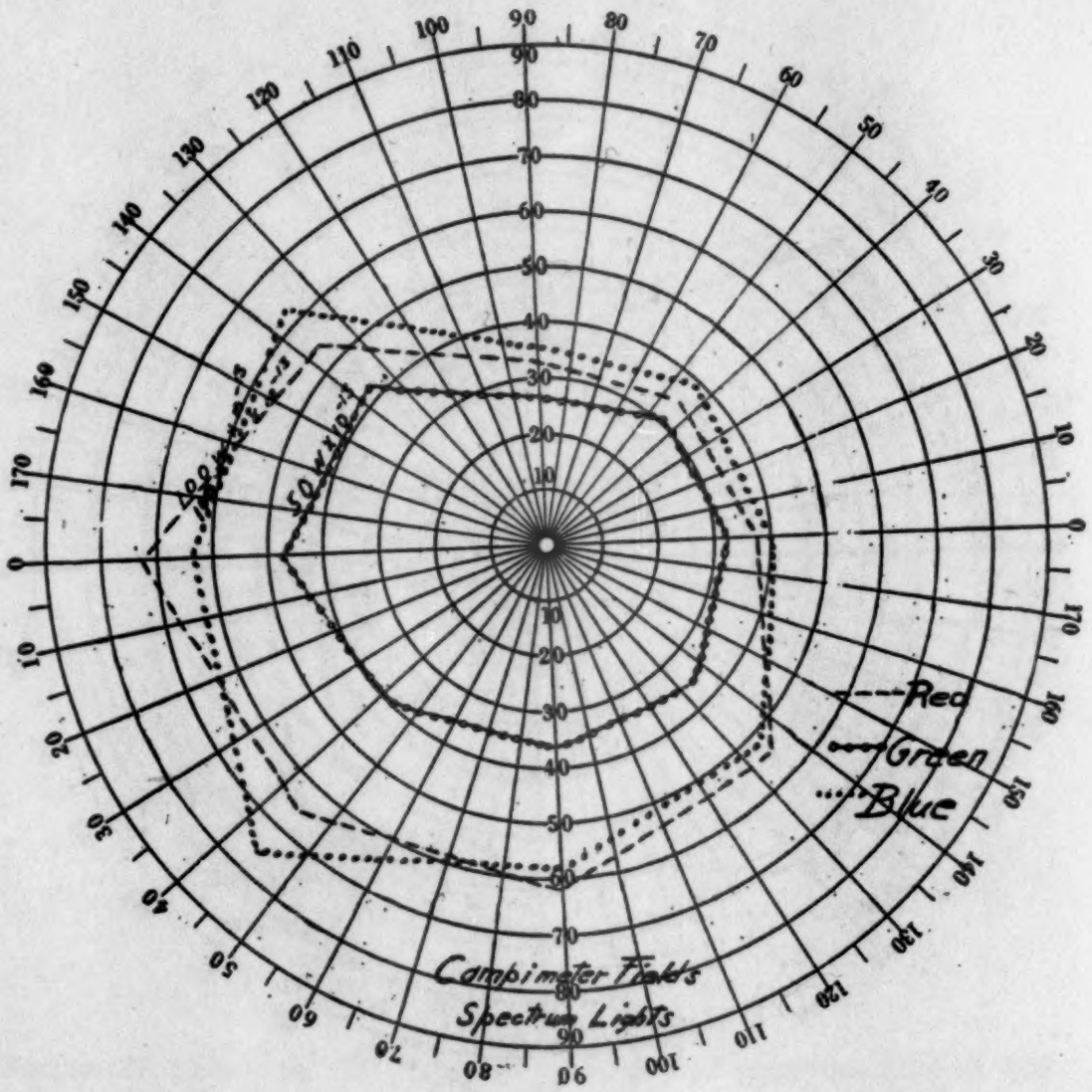


FIG. 27 B.

of ranking as to breadth both on the order of magnitudes of intensity and on the relative intensities of the stimuli employed; and that interlacing is the normal condition when stimuli of approximately equal energy are used.

In order to bring out these points still more clearly, certain groupings of the field maps given above have been made to show

(a) for three intensities of the red stimulus, the intensities of

the blue stimulus which will give fields that are smaller, larger and interlacing as compared with the fields for the red stimuli;

(b) for three intensities of the blue stimulus, the intensities of the red stimulus which will give fields that are smaller, larger and interlacing as compared with the field for the blue stimuli; and

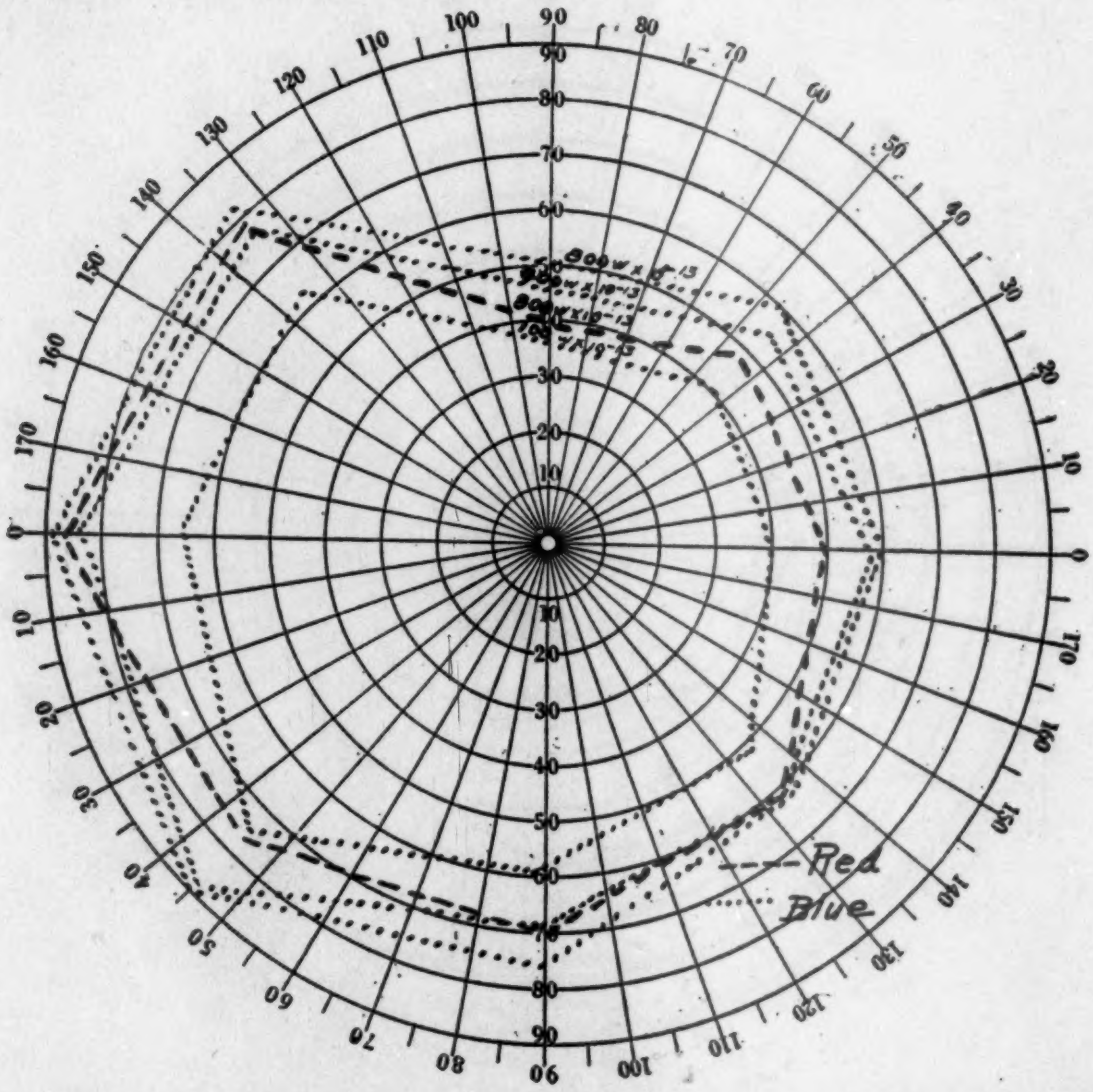


FIGURE 28. Showing the limits of sensitivity to spectrum red of 800 watts x 10^{-13}, and the limits for those intensities of spectrum blue which give smaller, interlacing and wider limits. These intensities of the blue stimulus are respectively 100, 400, and 800 watts x 10^{-13}.

(c) for one intensity of the blue stimulus, the intensities of the green stimulus which will give fields that are smaller, larger and interlacing as compared with the fields for the blue stimuli.

For (a) and (b) the three intensities selected were 25, 100 and 800 watts x 10^{-13}. The second of these values was, it will

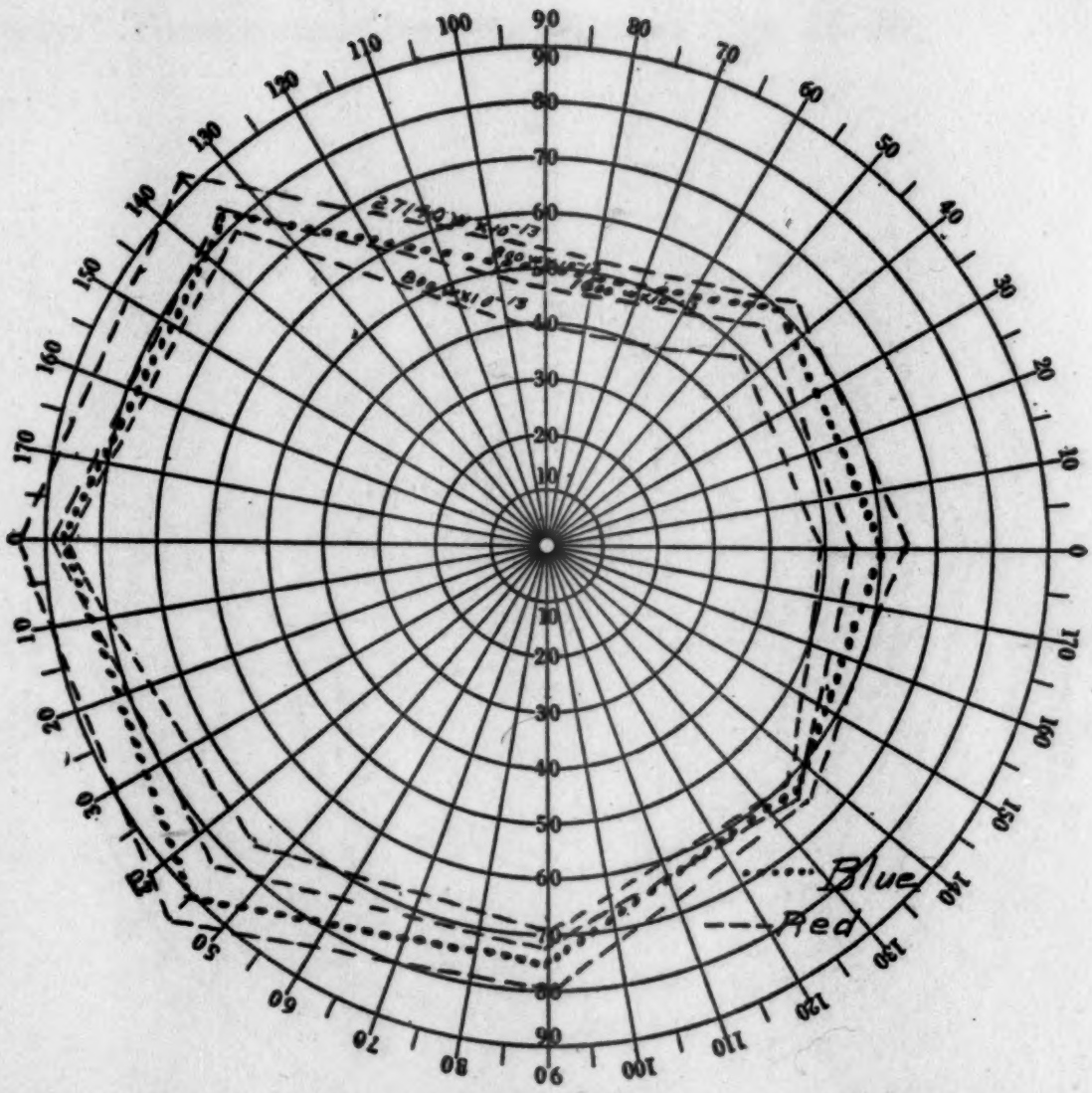


FIGURE 29. Showing the limits of sensitivity to spectrum blue of 800 watts x 10^{-13}, and the limits for those intensities of spectrum red which give smaller, interlacing and wider limits. These intensities of the red stimulus are respectively 800, 1600 and 27140 watts x 10^{-13}.

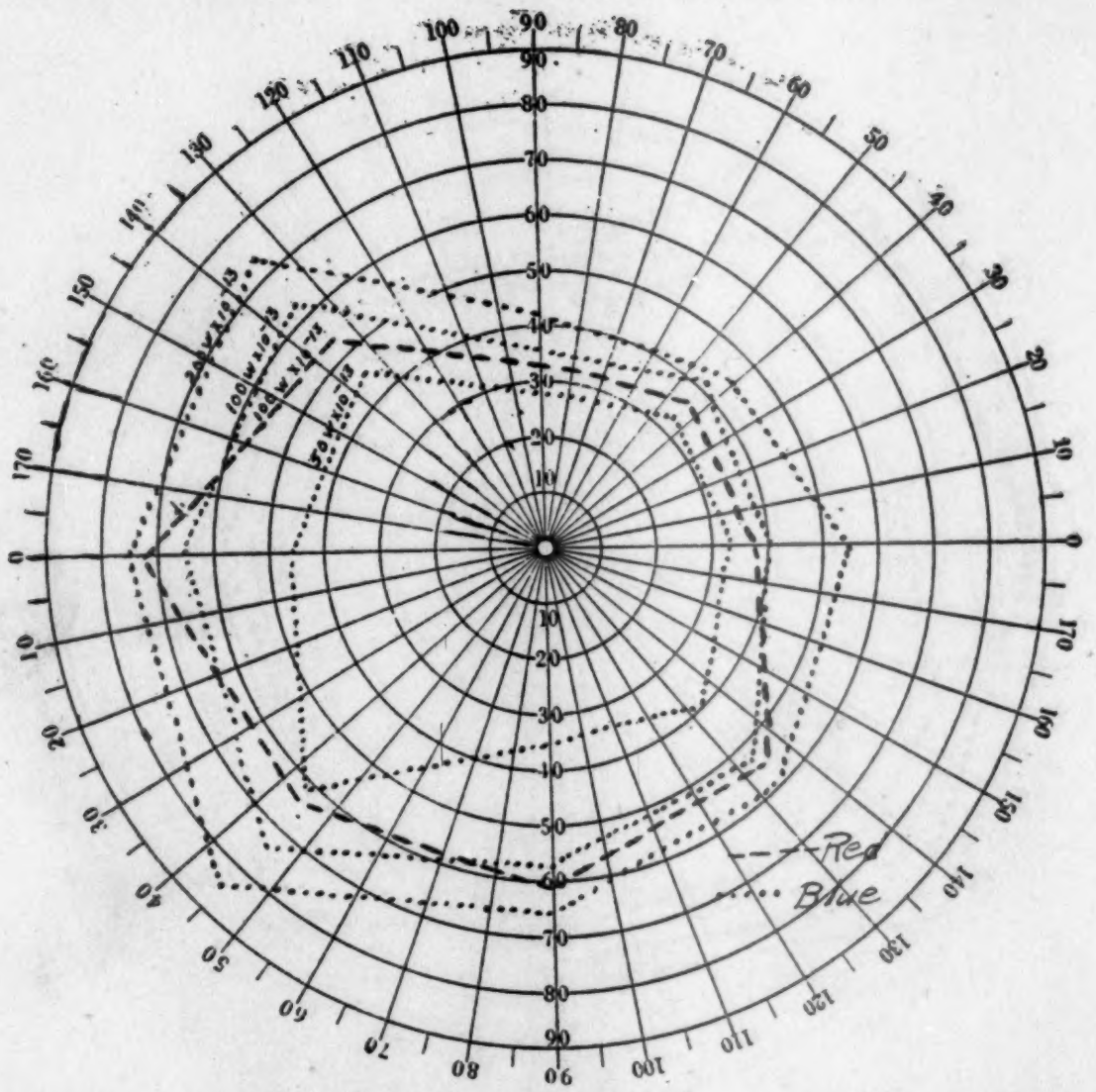


FIGURE 30. Showing the limits of sensitivity to spectrum red of 100 watts x 10^{-13}, and the limits for those intensities of spectrum blue which give smaller, interlacing and wider limits. These intensities of the blue stimulus are respectively 50, 100, and 200 watts x 10^{-13}.

be remembered, the intensity of spectrum light which gives fields most nearly equal in size to those obtained with the pigment stimuli of standard clinical usage. In (c) the comparison was made for blue and green because these colors are supposed by some clinicians to give the widest and narrowest fields respectively. These comparisons are given in Figs. 28–34.

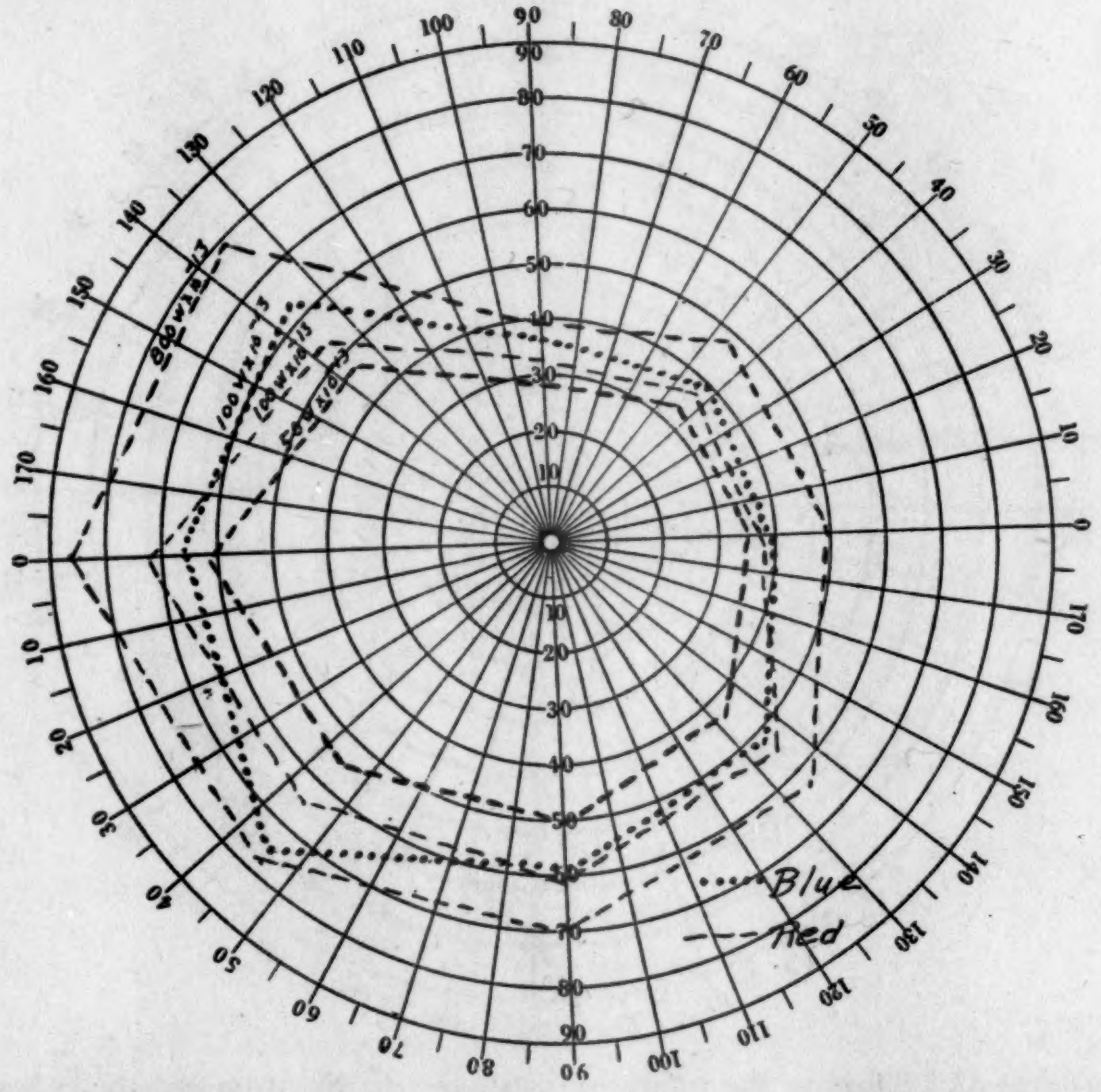


FIGURE 31. Showing the limits of sensitivity to spectrum blue of 100 watts x 10^{-13}, and the limits for those intensities of spectrum red which give smaller, interlacing and wider limits. These intensities of the red stimulus are respectively 50, 100, and 800 watts x 10^{-13}.

One further implication of our investigation of the chromatic sensitivity of the retina to the studies made in the clinic for purposes of diagnosis may be pointed out. These studies are as yet limited exclusively to perimetry. In perimetry data are obtained only at one point in each quadrant, namely, the point at which

the comparatively weak stimulus used is of threshold value. A consideration of how little of the information as to the variation in distribution of sensitivity over the retina which has been disclosed by the present study, would have been obtained by perimetry conveys some idea of what would be missed that might be

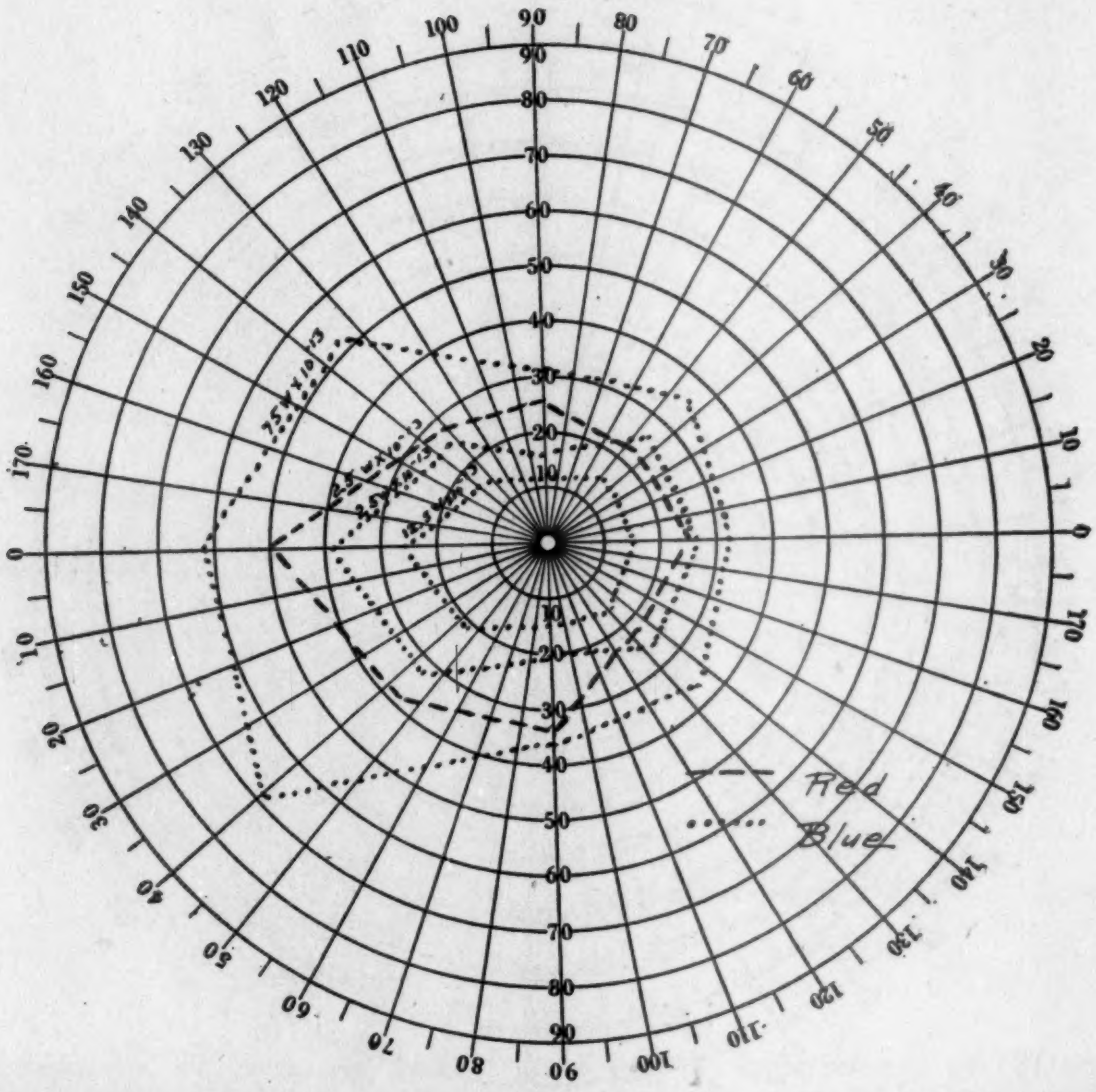


FIGURE 32. Showing the limits of sensitivity to spectrum red of 25 watts x 10^{-13}, and the limits for these intensities of spectrum blue which give smaller, interlacing and wider limits. These intensities of the blue stimulus are respectively 12.5, 25 and 75 watts x 10^{-13}.

of importance in diagnosis. With the stimuli of fixed and comparatively low intensity that are used in perimetry, small depressions in sensitivity would be passed over entirely; larger ones might appear as totally insensitive areas and be interpreted as either scotomata or significant cuts in the field; and parts of the retina which may have important diagnostic significance would be

left without examination. Just how valuable a more complete canvass of the chromatic response of the retina from center to periphery would be to the clinician, and the best method of making this study, are points for further investigation.

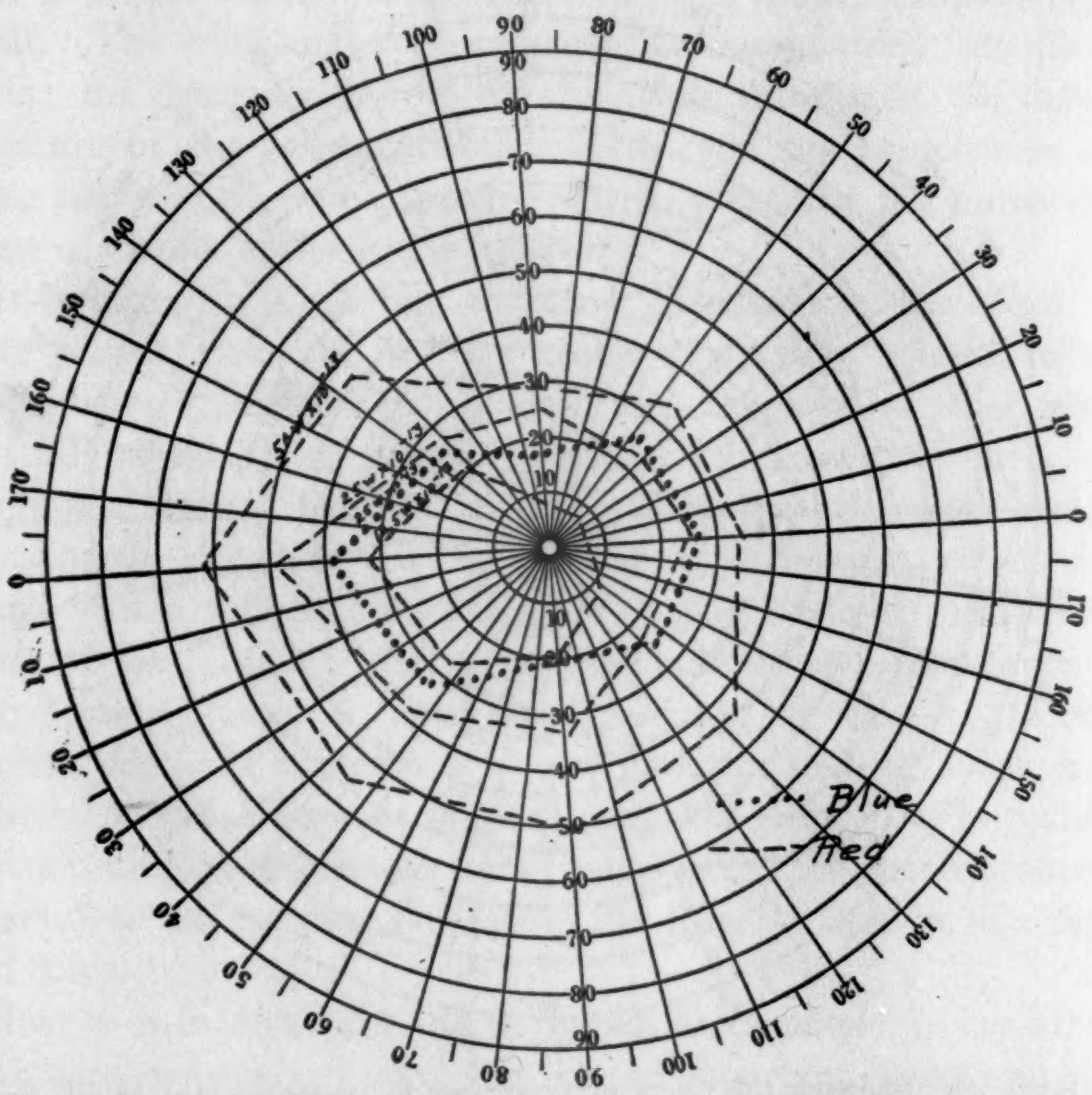


FIGURE 33. Showing the limits of sensitivity to spectrum blue of 25 watts x 10^{-13}, and the limits for those intensities of spectrum red which give smaller, interlacing and wider limits. These intensities of the red stimulus are respectively 12.5, 25 and 50 watts x 10^{-13}.

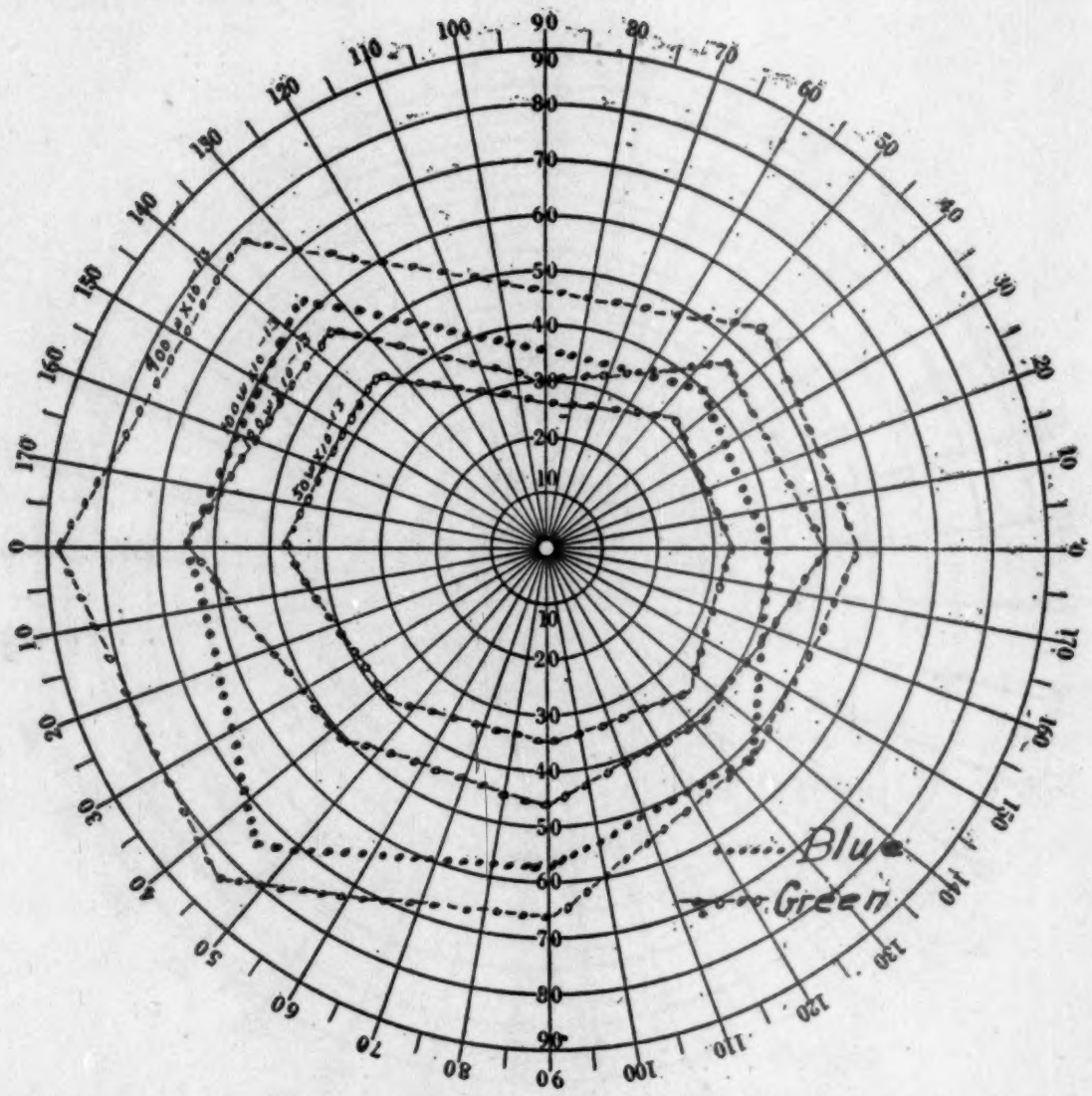


FIGURE 34. Showing the limits of sensitivity to spectrum blue of 100 watts x 10^{-13}, and the limits for those intensities of spectrum green which give smaller, interlacing and wider limits. These intensities of the green stimulus are respectively 50, 100 and 400 watts x 10^{-13}.

B. Dark Adaptation.

The sensitivity of the eye to the four spectrum stimuli used in light adaptation was also determined under conditions of complete dark adaptation from center to periphery of the field in the four principal meridional quadrants, upper, lower, temporal and nasal. The work under dark adaptation was divided into three parts: the determination of the chromatic thresholds, the determination of the achromatic thresholds, and the comparison of these two sets of results from point to point for the numerical value of the photochromatic interval.

It is especially important to know, for example, the effect of state of adaptation on the chromatic sensitivity of the retina from center to periphery in relation to perimetry and other types of study of the visual field for diagnostic and practical purposes. Prominent among the lines of interest in the achromatic sensitivity of the eye under dark adaptation is the interest in the minimum visible for the different wave-lengths of light in different parts of the retina. Another item of interest and importance in a systematic study of the retina's response to wave-length and intensity of light is the point on the intensity scale at which each of the qualitative changes in sensation takes place. An important division in this scale for the lower intensities is the photochromatic interval or the interval separating the threshold points for light and color.

Just as it is important and desirable, for example, to lay off or designate on a scale of wave-lengths the important changes in hue, saturation and brightness of the visible spectrum, so is it equally important and desirable to designate some of the more significant points in these changes on the intensity scale. It scarcely needs to be noted that one of the most remarkable and interesting features of the eye's reaction to change of intensity of spectrum light is the series of qualitative changes which take place beginning with the achromatic at low and ending with achromatic at high. It is one of the purposes of this study to designate on an absolute scale of intensities for four important regions of the spectrum from center to periphery the first two significant points in this

series of changes, the beginning of the achromatic and the beginning of the chromatic.

1. *Chromatic Thresholds.*

The chromatic thresholds of sensation were determined under dark adaptation at intervals of 1°–2° within 5° of the fovea; at intervals of 5° from 5°–30°; and at intervals of 10° from 30° to the limits of peripheral vision in the four principal meridional quadrants, upper, lower, nasal and temporal. The values of these thresholds in watts x 10^{-13} are given in Tables 14–17 and are graphically represented in the form of curves in Figs. 35 and 36. In plotting these curves it was found that the

FIGURES 35–36. Curves showing the energy values of spectrum lights required just to arouse the chromatic sensation from center to periphery of the field in the 180° and 90° meridians, dark adaptation.

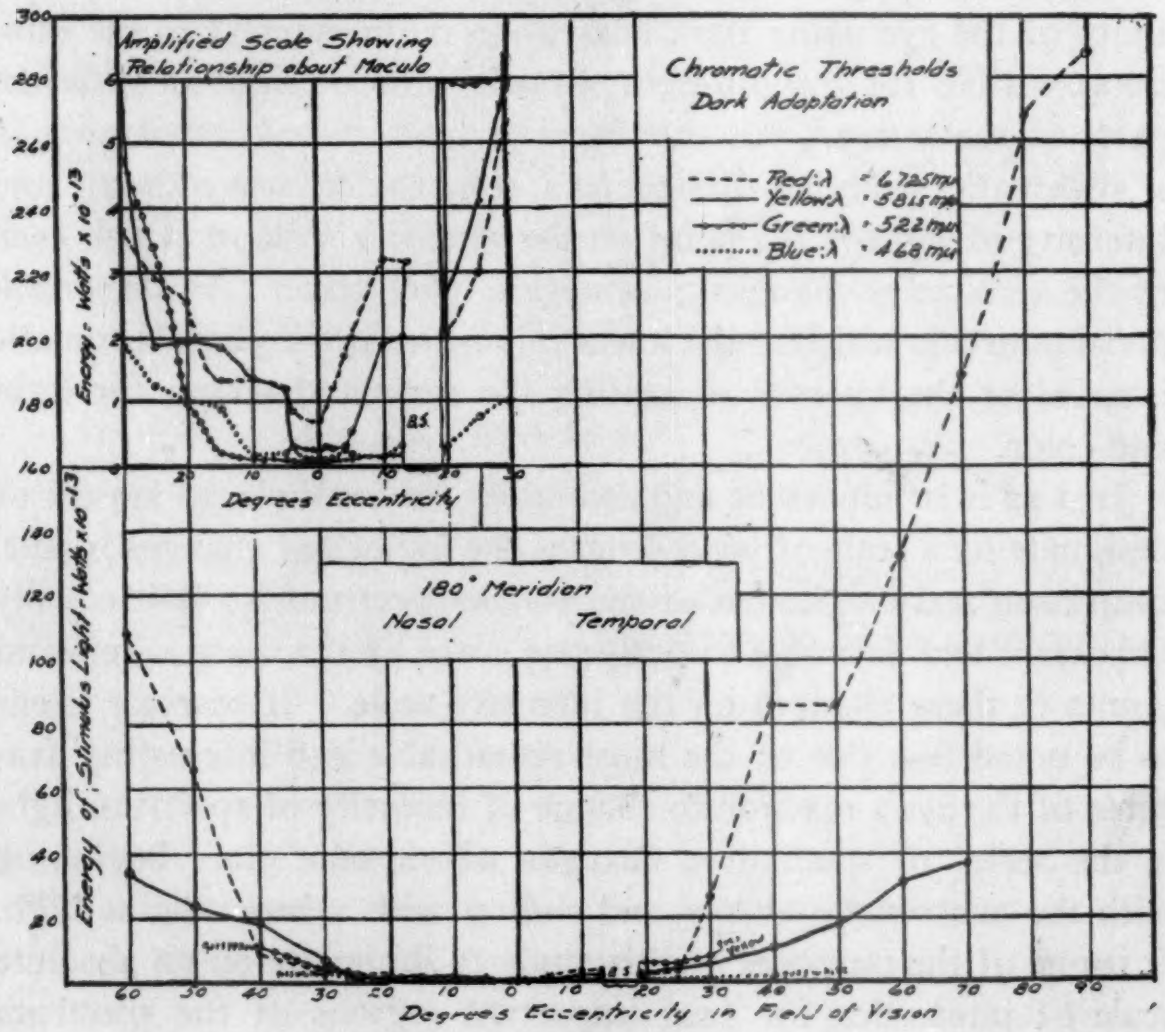

Amplified Scale Showing Relationship about Macula
Chromatic Thresholds Dark Adaptation
Red: λ = 672.5mμ
Yellow: λ = 581.5mμ
Green: λ = 522 mμ
Blue: λ = 468 mμ
Energy - Watts x 10⁻¹³
Degrees Eccentricity
180° Meridian
Nasal
Temporal
Energy of Stimulus Light - Watts x 10⁻¹³
Degrees Eccentricity in Field of Vision

FIG. 35

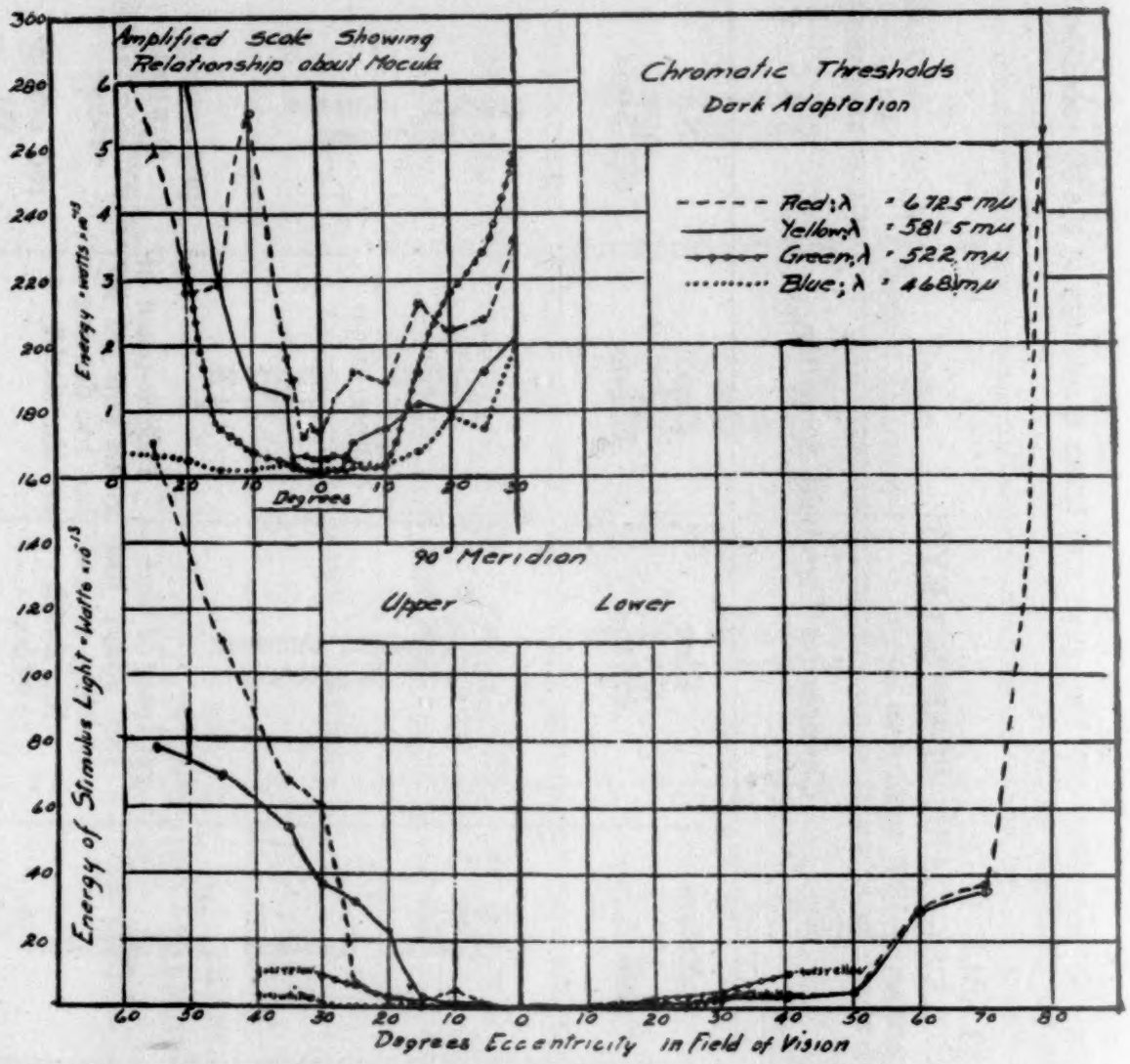


FIG. 36

large energy values of the thresholds at the periphery as compared with those at the center made it necessary to use a scale of representation which obscures the relatively small changes occurring in the central and paracentral regions. In order to show these changes, therefore, the threshold values within a radius of 30° of the center were in addition plotted on a scale magnified twenty times. The curves plotted on these amplified scales are shown in the insets given in the upper left-hand corner of Figs. 35 and 36. Further, to show still more clearly the variations in sensitivity which occur from point to point and from color to color in the central and paracentral regions of the retina, the data were plotted in the form of sensitivity curves. These curves are given in Fig. 37.

TABLES 14-17.
CHROMATIC THRESHOLDS, DARK ADAPTATION.

Showing the energy values of spectrum lights at the eye required just to arouse the chromatic sensation at nearlying points from center to periphery in the temporal and nasal quadrants of the 180° meridian, and the upper and lower quadrants of the 90° meridian. In these tables are included also the hue changes that occur in the threshold sensation.

TABLE 14
CHROMATIC THRESHOLDS—(DARK-ADAPTED EYE)
TEMPORAL QUADRANT—180° MERIDIAN

Degrees Eccentricity in Field of Vision	Amount of Light Entering Eye (Watts x 10^{-13})				Changes in Threshold Sensation			
	Yellow $\lambda =$ 581.5 mμ	Blue $\lambda =$ 468 mμ	Green $\lambda =$ 522 mμ	Red $\lambda =$ 672.5 mμ	Yellow $\lambda =$ 581.5 mμ	Blue $\lambda =$ 468 mμ	Green $\lambda =$ 522 mμ	Red $\lambda =$ 672.5 mμ
0°	0.2781	0.1170	0.0872	0.7123	gradual increase in brightness.	gradual increase in brightness	gradual increase in apple green brightness	gradual increase in brightness very pale pink
1°	0.3265	0.1170	..	0.9783				
2°	0.2902	0.1516	0.1006	1.2272				
4°	0.3386	0.2708	0.1073	1.7250				
5°	0.5563	0.1993	0.1141	2.0082				
6°	..	..	0.1476	..				
10°	1.8986	0.1473	0.1811	3.2097				
13°	2.0074	0.3271	0.2013	3.175				pink-orange (apricot)
19°	2.7330	0.3271	6.1052	2.008				deep yellow-orange
20°	2.7330	0.3596	6.1052	2.008				orange
25°	4.1116	0.7863	5.9039	2.995				
30°	5.9014	1.0062	7.8492	27.334				red orange
40°	10.8232	1.8216	..	86.387		get trace of blue—but adapt too quickly to get threshold white	Yellow-trace of green out to 50° but too fleeting to get threshold	do
50°	18.0548	..	..	86.387				do
60°	31.5748	..	..	132.473				deep orange
70°	37.7785	..	..	188.083				
80°	..	..	..	268.063				
90°	..	..	..	288.510				

TABLE 15

CHROMATIC THRESHOLDS—(DARK-ADAPTED EYE)

NASAL QUADRANT—180° MERIDIAN

Degrees Eccentricity in Field of Vision	Amount of Light Entering Eye (Watts x 10^{-13})				Changes in Threshold Sensation			
	Yellow $\lambda=$ 581.5 mμ	Blue $\lambda=$ 468 mμ	Green $\lambda=$ 522 mμ	Red $\lambda=$ 672.5 mμ	Yellow $\lambda=$ 581.5 mμ	Blue $\lambda=$ 468 mμ	Green $\lambda=$ 522 mμ	Red $\lambda=$ 672.5 mμ
0°	0.2781	0.1170	0.0872	0.7123	gradual increase in brightness	gradual increase in brightness	gradual increase in brightness	gradual increase in brightness
1°	0.2781	0.1213	..	0.729				
2°	0.2902	0.1278	0.0939	0.729				
4°	0.3144	0.3271	0.0939	0.893				
5°	1.2214	0.2058	0.1006	1.210				
10°	1.3906	0.1993	0.1208	1.322				
15°	1.8502	0.8946	0.2214	1.322				
20°	1.9343	1.0852	0.9929	2.574				
25°	1.8986	1.2411	3.4283	2.918				
30°	6.3609	1.8931	4.7768	3.690				
40°	18.7078	..	11.4724	8.582		white	slightly yellow green	yellowish-red red
50°	24.1860	..	..	66.081			greenish yellow yellow	yellow—then red do
60°	33.8604	..	..	108.133				

TABLE 16

CHROMATIC THRESHOLDS—(DARK-ADAPTED EYE)

UPPER QUADRANT—90° MERIDIAN

Degrees Eccentricity in Field of Vision	Amount of Light Entering Eye (Watts x 10^{-13})				Changes in Threshold Sensation			
	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ
0°	0.2781	0.1170	0.8722	0.7123	gradual increase in brightness	gradual increase in brightness white	gradual increase in brightness yellow	gradual increase in brightness
1°	0.2781	..	..	0.8496				
2°	0.3265	0.1430	0.1006	0.6179				
3°	..	..	0.1151	..				
4°	0.3023	0.2426	0.1208	1.5276				
5°	1.2093	0.2166	0.2013	1.8194				
10°	1.3907	0.1213	0.3824	5.5226				
15°	3.0353	0.1105	0.7246	2.9179				
20°	23.5814	0.2426	3.2203	2.8380				
25°	32.0465	0.3011	6.2528	7.466				
30°	37.1255	0.3661	9.3859	61.705				
35°	54.2976	*1.0397	..	68.570				
45°	69.6557	..	..	111.566				
55°	77.8789	..	..	171.640				
		*32° out on meridian						

TABLE 17

CHROMATIC THRESHOLDS—(DARK-ADAPTED EYE)

LOWER QUADRANT—90° MERIDIAN

Degrees Eccentricity in Field of Vision	Amount of Light Entering Eye (Watts x 10^{13})				Changes in Threshold Sensation			
	Yellow $\lambda=$ 581.5 mμ	Blue $\lambda=$ 468 mμ	Green $\lambda=$ 522 mμ	Red $\lambda=$ 672.5 mμ	Yellow $\lambda=$ 581.5 mμ	Blue $\lambda=$ 468 mμ	Green $\lambda=$ 522 mμ	Red $\lambda=$ 672.5 mμ
0°	0.2781	0.1170	0.0872	0.7123	gradual increase in brightness	gradual increase in brightness	gradual increase in brightness	gradual increase in brightness
1°	0.2781	0.1170	0.1006	0.9783				
2°	0.3265	0.1213	0.1073	1.2787				
3°	..	0.1430	..	..				
4°	0.3203	0.3206	0.1208	1.442				
5°	0.5200	0.2187	0.1476	1.665				
10°	0.7374	0.1993	0.1946	1.442				
15°	1.1126	0.4061	1.6399	2.686				
20°	1.0057	0.9053	2.8044	2.267				
25°	1.6134	0.7320	3.4283	2.420				
30°	2.1163	2.1703	4.9177	3.630				
40°	2.8781	..	10.1977	4.566				
50°	4.8251	..	..	4.626				
60°	28.7572	..	..	30.637				
70°	35.0100	..	..	37.589				
80°	..	..	..	264.154				

light pink-orange

white

green-goes yellow almost instantly yellow

yellow—then red

The study of the chromatic thresholds of sensitivity for the dark-adapted eye has, it may be noted, systematic interest chiefly in relation to the photochromatic interval, the effect of state of adaptation on retinal sensitivity, and the practical problem of dark room perimetry. All of these will be discussed in later chapters. In addition the following summary of results may be of interest here:

(1) *The region sensitive to color does not extend to the periphery of the field for all wave-lengths, as is the case with light adaptation.* Furthermore, this region shows a general tendency to vary with the wave-length of the stimulus. That is, red is seen to the limit of white light vision in all quadrants; the sensitivity to yellow does not extend to the peripheral limit of vision in the temporal quadrant; and green and blue can not be sensed beyond 40° in any quadrant, whatever the intensity of the stimulus. In the lower and nasal quadrants the sensitivity to blue is less extensive than that to green; in the upper and temporal quadrants the reverse is true.

It may be noted here that the loss in color of the blue and green stimuli occurs at points where a sudden increase in energy was required to give the chromatic threshold under light adaptation. It is not surprising to find that under the unfavorable conditions for blue and green resulting from dark adaptation sensitivity to these colors should end at these points. This selective effect of the conditions found in dark room work on chromatic sensitivity to wave-length will be discussed more fully in the section on the effect of state of adaptation on the chromatic sensitivity of the retina. This much, however, may be noted here. There is a tendency for blue and green on passing into the periphery of the retina to lighten, and for red and yellow to darken. Moreover, a black preexposure and surrounding field are unavoidable with dark adaptation. This condition tends through contrast and after-image effects to add white to the stimulus color, enhancing thereby the tendency for blue and green to lighten and counteracting the tendency for red and yellow to darken. As the result of these contrast and after-image effects which are always emphasized in the peripheral field, blue and green tend towards white

as the periphery is approached, while red and yellow remain of nearly the same brightness from center to periphery.

(2) *Threshold blue and yellow show no change in hue, merely a change in brightness from the center to the periphery of the field. Threshold red and green on the other hand tend to become*

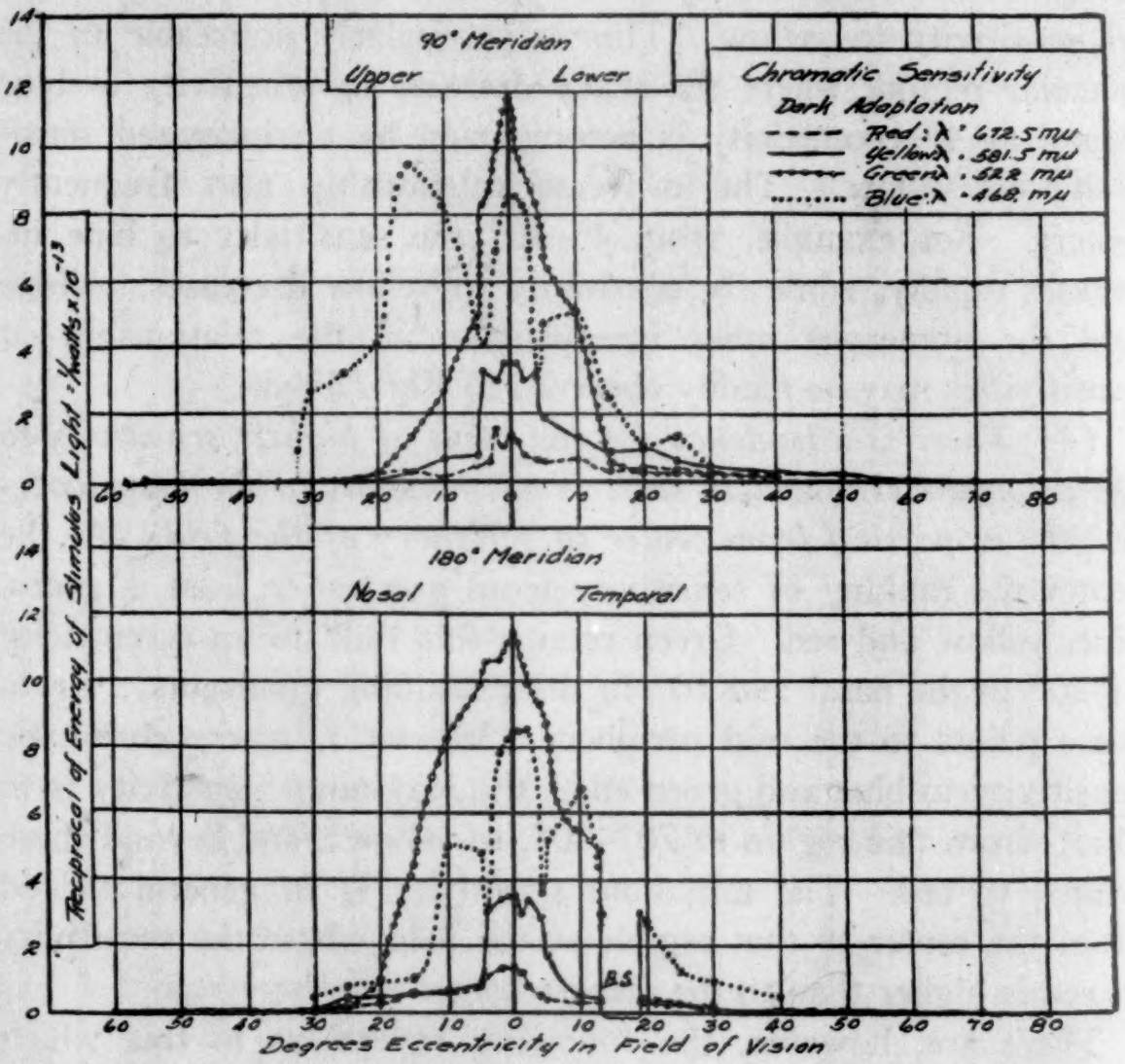


FIGURE 37. Curves showing the chromatic sensitivity to spectrum lights from center to periphery of the field in the 180° and 90° meridians, dark adaptation.

yellow. Green tends towards yellow and then white in the mid periphery. Red tends towards orange as the center is receded from, and in the far periphery is seen first as yellow, then as red, as the stimulus is increased to the threshold value.

(3) *Great irregularity in the ratio of sensitivity to the different colors occurs from point to point in the field.* Small areas are found in which there is a marked decrease in sensitivity to one

color with no corresponding decrease in sensitivity to the other three. For example, at 10° in the upper and 15° in the lower vertical meridional quadrants there is a sudden rise in the threshold curve for red with no corresponding change in the curves for yellow, green and blue. Where a decrease in sensitivity to blue is found, however, there is frequently an increase of sensitivity to yellow. This is particularly noticeable in the macular region, where the sharp decrease in sensitivity to blue found at 4° eccentricity is accompanied by an increased sensitivity to yellow. The converse relationship also frequently occurs. For example, from 4°–10° the sensitivity to blue increases rapidly, while the sensitivity to yellow decreases. These and the numerous other irregularities in the relationship of sensitivities may be readily observed in Figs. 35–36.

(4) *There is a tendency for the point of highest sensitivity to the colors investigated to shift from the short to the long wavelengths in passing from center to periphery of the field.* At the center the ranking of sensitivity from greatest to least is green, blue, yellow and red. Green retains this rank to an eccentricity of 20° in the nasal and 10° in the remaining quadrants. From these points to the mid periphery (30°–40°), where chromatic sensitivity to blue and green ends, the maximum sensitivity is to blue; from this region to 70°–80°, to yellow; and beyond these points, to red. The minimum sensitivity is in general to red from the center to that region of the field where the sensitivity to red is higher than to the other colors.

There are, however, the following exceptions to this which should be noted: (a) from 15°–25° in the upper quadrant, at 50° in the lower quadrant, and from 5°–15° and 30°–40° in the nasal quadrant, in which cases the lowest sensitivity is to yellow; and (b) from 20°–30° in the lower quadrant and from the peripheral edge of the blind spot to 20° in the temporal quadrant, in which cases it lies in the green. These variations in the position of maximum and minimum sensitivity to the stimuli investigated in different parts of the field are shown graphically in Fig. 12, column 2, for one meridian selected as typical. The data from which these curves were drawn are given in Table 18.

TABLE 18.
CHROMATIC SENSITIVITY, DARK ADAPTATION.

Showing the chromatic sensitivity to the four spectrum lights expressed as the reciprocal of the energy of the stimulus required just to arouse the chromatic sensation at the points selected in the temporal and nasal quadrants of the 180° meridian and the upper and lower quadrants of the 90° meridian. Included also are ratios of sensitivity to the different colors when the maximum sensitivity at each point is taken as unity.

Degrees Eccentricity in Field of Vision	Temporal Quadrant—180° Meridian								Nasal Quadrant—180° Meridian							
	Sensitivity				Ratio				Sensitivity				Ratio			
	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ
0°	3.60	8.55	11.47	1.40	0.31	0.75	1.00	0.12	3.60	8.55	11.47	1.40	0.31	0.75	1.00	0.12
10°	0.53	6.79	5.52	0.31	0.08	1.00	0.87	0.05	0.72	5.02	8.29	0.76	0.08	0.63	1.00	0.09
20°	0.37	2.78	0.16	0.50	0.13	1.00	0.06	0.18	0.52	0.92	1.00	0.39	0.52	0.92	1.00	0.39
30°	0.17	0.99	0.12	0.036	0.17	1.00	0.12	0.04	0.16	0.52	0.21	0.27	0.31	1.00	1.00	0.52
40°	0.092	0.55	....	0.011	0.17	1.00	....	0.02	0.053	....	0.087	0.116	0.45	....	0.75	1.00
50°	0.055	....	....	0.011	1.00	....	....	0.02	0.041	....	....	0.015	1.00	....	....	0.36
60°	0.031	....	....	0.007	1.00	....	....	0.22	0.029	....	....	0.009	1.00	....	....	0.31
70°	0.026	....	....	0.005	1.00	....	....	1.00	....	....	....	....	....	....	....	....
80°	....	....	....	0.003	....	....	....	1.00	....	....	....	....	....	....	....	....
90°	....	....	....	0.003	....	....	....	1.00	....	....	....	....	....	....	....	....

	Upper Quadrant—90° Meridian								Lower Quadrant—90° Meridian							
	Sensitivity				Ratio				Sensitivity				Ratio			
	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ
0°	3.60	8.55	11.47	1.40	0.31	0.75	1.00	0.12	3.60	8.55	11.47	1.40	0.31	0.75	1.00	0.12
10°	0.72	8.25	2.62	0.18	0.08	1.00	0.32	0.02	1.36	5.02	5.14	0.69	0.26	0.98	1.00	0.13
20°	0.04	4.12	0.31	0.35	0.01	1.00	0.08	0.09	1.00	1.10	0.36	0.44	0.91	1.00	0.33	0.40
30°	0.03	2.73	0.11	0.02	0.01	1.00	0.04	0.01	0.47	0.46	0.20	0.27	1.00	0.98	0.42	0.57
40°	0.014*	....	....	0.008*	1.00*	....	....	0.57*	0.35	....	0.10	0.22	1.00	....	0.28	0.63
50°	0.012†	....	....	0.005†	1.00†	....	....	0.41†	0.21	....	....	0.22	0.96	....	....	1.00
60°	....	....	....	....	....	....	....	....	0.034	....	....	0.032	1.00	....	....	0.94
70°	....	....	....	....	....	....	....	....	0.028	....	....	0.026	1.00	....	....	0.93

*=Sensitivity at 45° Eccentricity. †=Sensitivity at 55° Eccentricity.

(5) *The rate of decrease of sensitivity from center to periphery varies for the different colors.* It is particularly noticeable that the rate of change is very different for the paired colors. For example, the sensitivity to red and green decreases at first rapidly, then slowly to the limit of sensitivity. The curve for green, however, has a much steeper slope than that for red. The point of highest sensitivity for both colors is at the center with one exception,—red in the upper vertical quadrant. Here the highest sensitivity is found at a point 3° from the center. The sensitivity to blue and yellow changes very irregularly, particularly in the region of the macula. As has been stated above, the sensitivity to blue decreases rapidly for the first 4° from the center; then increase to 10°, where it rises to a value nearly as high as at the center, from which point it decreases again rapidly and continuously to the limit of sensitivity. At 15° in the upper quadrant the sensitivity to blue is at its highest level. Sensitivity to yellow, however, decreases slightly for the first 2° from the center; from 2°–4°, the position of sharp decrease in sensitivity to blue, it increases; from 4°–10° it decreases again rapidly and from 10° to the limits of the field it decreases slowly.

If a decreased sensitivity to blue and a correspondingly increased sensitivity to yellow in the macular region is the result of yellow pigmentation, as has been suggested by previous writers, these results would indicate that there is a faint pigmentation immediately around the fovea which increases to a dense, well-defined ring of pigmentation approximately 4° from the fovea, and that the region 10°–15° from the fovea is relatively free from pigmentation. A verification of this is of course impossible with a living eye. An ophthalmoscopic examination of the eye under investigation yielded negative results. A photograph of the fundus, however, revealed some interesting points that may have significance. The photograph was made with a Zeiss-Nordensen camera at the Wills Eye Hospital, Philadelphia, by Dr. Alfred Cowan, for whose interest and coöperation on this point the writer wishes to express her very great appreciation.

The photograph of the central portion of the fundus is shown

in Fig. 38. At the extreme left of the picture will be seen the edge of the optic disc or papilla; at the center, three small bright discs, corneal and lenticular reflexes; slightly below these and to the right a dark spot, the fovea centralis; and encircling the fovea at a distance of approximately 4° a clearly defined light ring which may perhaps be considered to represent a zone of dense macular pigmentation. In any event its location and extent correspond closely with the zone of decreased sensitivity to blue

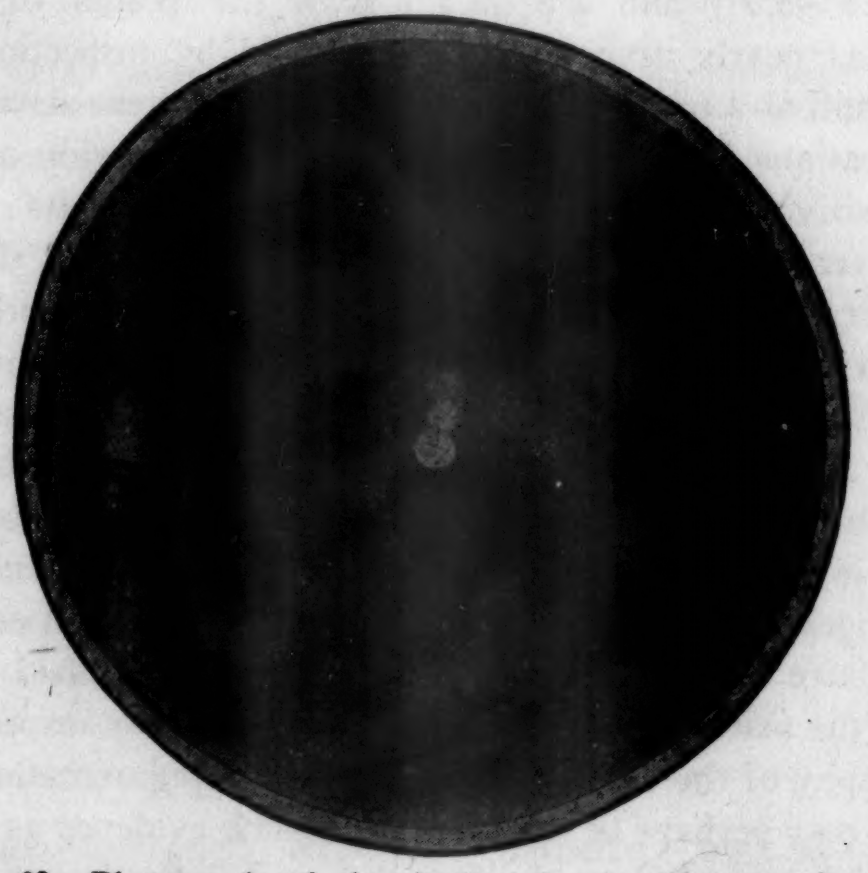


FIGURE 38. Photograph of the fundus showing the macular reflex.

and increased sensitivity to yellow. A second less clearly defined ring will be noticed concentric with the first at a distance of about 6°–8° from the fovea. As no threshold determinations were made in the region corresponding to this second ring, it is impossible to determine from our data whether or not it sustains any relation to the anomalies in sensitivity to blue and yellow.

The coincidence of the inner ring with the zone of anomalous sensitivity to blue and yellow was ascertained as follows: The distance from the inner edge of the blind spot to the fovea was determined in degrees on the Ferree-Rand perimeter for the eye

in question, and the corresponding distance in the photograph was measured in millimeters by means of vernier calipers reading to tenths of a mm. From these two values a scale of relationship was determined from which the distance of the ring from the fovea could roughly be converted into degrees. The distances between the fovea and the inner and outer edges of the ring in the four principal meridional quadrants, nasal, temporal, upper and lower, were found to be respectively 2.8°–4.5°, 3.8°–5.3°, 3.5°–5.9°, and 2.8°–3.5°, with the points of greatest density as nearly as could be determined by inspection of the photograph at 3.6°, 4.8°, 4.6° and 3.1°. That the deviations of these locations from exact coincidence with the region of anomalous sensitivity to blue and yellow fall within the limits of experimental error may be inferred with a reasonable degree of probability from a consideration of the conditions under which the latter were determined, *i.e.*, a 1° stimulus was used in making the threshold determinations and no determinations were made between 2° and 4° and between 4° and 5° from the center of the field. In this connection, however, it must be remembered that at best only a relationship between a photographed macular reflex and changes in sensitivity to blue and yellow has been established by the above comparison. It has yet to be determined definitely whether the macular reflexes which are revealed by inspection and photography of the fundus are due to yellow pigmentation. That they are may perhaps be inferred from such evidence as has been presented here and from the fact that such reflexes are found to be more frequent and more pronounced in the races which are known to have a heavy macular pigmentation. The results given here are presented primarily as an interesting coincidence, to be evaluated in due course along with other indirect and corroborative data.

The only other measurements of the chromatic threshold under dark adaptation that have as yet been published, so far as the writer is aware, are those of Monroe and Almack for central vision. Monroe (**81**) determined the chromatic threshold for seven regions of the spectrum for 20 observers. A stimulus subtending a visual angle of 2°2.2′ was used. Almack (**56**), in a

quantitative study of chromatic adaptation, determined the threshold value for four spectrum lights. Her stimulus subtended a visual angle of 5°44′, a stimulus of this magnitude being needed to provide an area sufficiently large for consistency of result in experiments in adaptation. Monroe's, Almack's and the writer's investigations differ in respect not only to the size of stimulus used, but also to the wave-lengths selected. However, it may be of some importance and interest to compare the values obtained

TABLE 19.

Showing the energy value of spectrum lights at the eye (in watts x 10^{-13}) required just to arouse the chromatic sensation under dark adaptation, as determined by Monroe, Almack and Wentworth.

Monroe, 20 observers (2°2.2′ stimulus)			Almack (5°44′ stimulus)		Wentworth (1°16′ stimulus)	
Wave-length	Threshold value		Wave-length	Threshold value	Wave-length	Threshold value
	Median	Range				
655 mμ	1.59	4.6 — .597	670 mμ	45.04	672 mμ	.712
616 mμ	1.66	31.1 — .54				
580 mμ	43.2	528. —11.9	579 mμ	2.10	581 mμ	.278
552 mμ	.127	6.21— .077				
522 mμ	.436	6.03— .042	515 mμ	1.595	522 mμ	.087
489 mμ	4.60	31.6 — .299				
463 mμ	3.29	30.7 — .298	466 mμ	20.132	468 mμ	.117

in the three investigations. This comparison may be made from the data given in Table 19.

It is seen from this table that the writer's threshold determinations in all cases except yellow fall near the lower end of the range given by Monroe's observers for approximately the same wave-lengths. For yellow the value for the writer's threshold is somewhat lower than any found by Monroe. The order of sensitivity from greatest to least for Monroe's observers on the average was for the four principal colors: green, red, blue, yellow; for Almack: green, yellow, blue, red; for Wentworth: green, blue, yellow, red. For Monroe's individual observers the order of sensitivity is not the same for the four colors.

Aside from individual differences in color sensitivity, the following reasons may be suggested for the differences in the three sets of results:

(a) the difference in the wave-lengths investigated, particularly in the red of the spectrum;

(b) the difference in size of stimulus used; and

(c) the difficulty experienced by some observers in making the determination of the yellow threshold, which is discussed by Monroe. That is, the transition from the achromatic to the chromatic stage of the sensation aroused by weak yellow light is apparently more difficult to make by the average observer for this than for the other colors.

II. *Achromatic Thresholds.*

The studies that have been made of the achromatic threshold or the minimum visible may be divided into two classes: (a) determinations of the minimum visible for central vision; and (b) determinations of the minimum visible at various points in the peripheral field. Among the investigations made for central vision may be mentioned the work of Ebert (83), Pflüger (84), Wien (85), Drude (86), Ives (87), Russell (88), Buisson (89), Reeves (90), Coblentz (91), and Monroe. Monroe (81) in 1925 reviewed in detail the investigations of this point preceding her own. In the conclusion of this review she states: "The above summary of work done by previous investigators shows disagreement both as to procedure and as to what shall be called 'the least radiation visually perceptible' or 'the minimum visible'. Lights differing greatly in composition have been used, spectrum and approximate white; and with one exception the energy value has been calculated indirectly from measurements made on some other source or computed by the use of a mechanical equivalent which expresses the relation of the photometric to the energy unit for some other source than the one used for the visual stimulus. And in case of this one exception the limit of visibility was taken from astronomical data on the visibility of stars, the estimates of which range from the sixth to the eighth magnitude, rather than having been experimentally determined.

" It would seem reasonable to assume that *the* minimum visible should mean the least amount of radiation visually perceptible of the wave-length or range of wave-lengths to which the eye is the most sensitive measured in absolute units. So defined, the essential conditions for its determination would be a careful search of the spectrum for this wave-length to which the eye is most sensitive, a determination of the limit of visibility with this wave-length, and the direct measurement of its energy. In the investigations cited above, one and sometimes two, but never all of these conditions, have been satisfied. Moreover, in no case, whatever the source of light chosen, has the energy been measured and an actual determination of the limit of visibility been made for the same light.

" By a still more rigid interpretation the determination of the minimum visible might also involve the satisfying of other and more difficult requirements such as the use of the most favorable time of exposure and size of field, the use of the most sensitive part of the retina, etc., all of which features would in all probability differ in value both for the wave-length of light employed and for the observer " (pp. 51–52).

Monroe determined for central vision the minimum visible, both chromatic and achromatic, at seven points in the spectrum for 20 observers. The apparatus and method used by her were similar to those employed in the present investigation. They differed only in the following regards: (a) a Nernst filament was used as the source of light; and (b) the stimulus subtended a visual angle of 2°2.2′. The values obtained for the achromatic threshold are as follows:

Stimulus	Energy of Achromatic Thresholds	Range of Values
Red (655 mμ)	626.99 watts x 10^{-16}	1209.27 –186.48 watts x 10^{-16}
Orange (616 mμ)	130.28 " "	273.77 – 70.72 " "
Yellow (580 mμ)	27.96 " "	49.04 – 11.56 " "
Yellow-green (553 mμ)	2.203 " "	3.24 – 0.718 " "
Green (522 mμ)	1.953 " "	3.469– 1.295 " "
Blue-green (489 mμ)	8.11 " "	13.8 – 2.96 " "
Blue (463 mμ)	15.62 " "	29.53 – 6.28 " "

A few attempts have been made to determine the achromatic thresholds in peripheral regions of the field, among them the

studies of Breuer and Pertz, von Kries and Eyster, Abney and Watson, and Jones. A brief review of these studies, in so far as they bear on the point in question, will be given here. It will be noted in this review that Monroe's general criticism of the work of her predecessors on the problem in central vision applies also to these investigations in the peripheral field.

In 1897 Breuer and Pertz under the direction of von Kries explored the paracentral field out to 4° in the nasal and temporal quadrants and made a cursory examination at 10° and 20°. Their scale of intensities was arbitrarily selected, based on variations in the distance of a gas flame of constant height from the test object. The light of the flame was filtered to bluish white. The work was done under conditions of dark adaptation. Breuer (92) found an increase in sensitivity toward the periphery which was rapid from 1°–4° around the fovea, then more gradual to a maximum between 10° and 20°, beyond which point there was a decrease. He apparently made little exploration beyond 20°, however, and no curves are given for points beyond 4°. In later experiments Pertz (93) explored the parafoveal area within a radius of 2.5° with red, blue and yellow light obtained with filters, and found the dark-adapted fovea to be slightly more sensitive to red light than this area. His curve for blue corresponds to that previously obtained for bluish white light, that is, the sensitivity from 0.75°–2.5° increases rapidly. The curve for yellow, on the other hand, shows a very slight increase in sensitivity in the parafoveal area.

In 1907 von Kries and Eyster (94), using monochromatic light, sought to determine the achromatic threshold not only with the wave-length to which the eye is most sensitive but also under the most favorable conditions of time of exposure, size of field and position of the retina used. They selected 507 mμ as the proper stimulus, apparently on the basis that this part of the spectrum had been found to give a maximum bleaching of the visual purple. Moreover, this wave-length fell within the range of wave-lengths to which König had found the eye to be most sensitive for a group of observers. Although von Kries and Eyster state that the peripheral retina was used, they give no

information as to the approximate meridian, or degree of eccentricity of the region of the retina stimulated, nor do they state in detail the method used in finding the point of greatest sensitivity. The source of light employed was a Hefner lamp, the radiations from which were reflected from a magnesium oxide surface into a spectroscope. The energy values were calculated from Ängstrom's data on the distribution of energy in the light from a Hefner lamp. Several field sizes were used but the optimum size of field used and the time of exposure giving the greatest sensitivity are not clear from their description. They state their results as follows:

"1. Für eine merkliche Erregung des Sehorgans ist bei Herstellung der günstigsten Bedingungen hinsichtlich Adaptation, Strahlungsart (507 mμ) raümlicher und zeitlicher Verhältnisse eine Energiemenge von 1,3–2,6 x 10^{-10} Erg. erforderlich.

"2. Für die Sichtbarkeit dauernd exponierter Objeckte ergibt sich bei günstigster Strahlungsart und güstigster raümlicher Anordnung eine Energiezuführung von ca, 5,6 x 10^{-10} Erg. pro Sekunde."

In 1916 Abney and Watson (95) published interesting results on the chromatic and achromatic thresholds for spectrum light at the fovea and at 1.25°, 2.5°, 5° and 10° in the lower vertical quadrant of the 90° meridian. Spectrum light from a Nernst filament was passed through an analyzing slit and focused on a magnesium oxide disc so arranged as to subtend a visual angle of 34′ at the eye. Intensities were cut down to threshold values by means of an annular wedge which had previously been corrected for selective absorption in different parts of the spectrum and calibrated so that calculation could be made of that fraction of the total light passing through the slit which fell on the disc for any wave-length and any setting of the wedge.

No direct measurements of energy were made. The intensity of the light falling on the disc when the slit was placed at the sodium line was determined by photometric comparison with a standard Hefner lamp and an arbitrary energy unit was selected such that an intensity of illumination on the disc of 1 lux (metercandle) was equal to 100,000 such units per square centimeter.

The relative distribution of energy in the spectrum used was obtained by means of a linear thermopile in terms of the deflections of a sensitive galvanometer. The energy of radiation falling on unit area of the disc could then be calculated in terms of the unit of intensity selected. The coefficient of reflection of the disc was obtained and the percentage of light reflected to the eye was determined.

The value of the threshold throughout the spectrum was determined for eight observers, completely dark-adapted. The fixation device consisted of a glass rod, one end of which, 1 mm. in diameter, was ground and transilluminated by dim red light. For observations in the central field the circuits were so arranged that pressure of a key cut off the fixation light and exposed the stimulus light simultaneously. Both eyes were used in making the observation.[1]

The observers were found to fall into two classes. In Class I there were three normal and two color-blind subjects, one of whom was a protanope (red-blind) and the other had a displaced green curve. In Class II there were two normal and one color-blind subject, a deuteranope (green-blind). The differences found between these two classes of observers are as follows: (1) In Class I the fovea was less sensitive than the parafoveal region. The greatest increase in sensitivity was found from 0–1.25°; a more gradual increase from 1.25°–10°. The amount of the increase varied with wave-length. Between 0° and 2.5° for 658 mμ, for example, it was in the relation of 1:1.14; for

[1] This was done after a preliminary test of results on binocular summation had been published by Piper. Piper had found that with a dark-adapted eye and stimuli near the threshold, binocular summation occurs. He states (a) that when a feebly illuminated surface was examined with both eyes it appeared nearly twice as bright as when only one eye was used, and (b) that the threshold values for the two eyes used together was about half those for either eye used separately. Abney and Watson determined the threshold value at the fovea for two observers and at 5° with each eye separately and with both eyes used together. They state as a result "that for the typical observer for any object subtending a visual angle of 34′ and momentary stimulation there is no evidence of binocular summation." They found that "the values were the same for the left and the right eye used separately and for the two eyes used together. Great difficulty was found, however, in making satisfactory settings when one eye alone was used, as it was difficult to adjust the accommodation so as to keep the fixation light always in focus."

415 mμ, in the relation of 1:27. In Class II the increased sensitivity of the parafoveal region was either less pronounced or entirely absent. At 2.5° the increase for 658 mμ was only 1.05 times and for 415 mμ 1.49 times,[1] that at 0°. (2) In Class I the chromatic and achromatic thresholds coincided for foveal vision; in Class II the fovea had a photochromatic interval for all colors except red.

In 1921 Wynn Jones (96) determined the minimum visible in the peripheral field for white light at 0°, 10°, 20°, 40°, and 60° in the nasal and temporal quadrants of the 180° meridian. Binocular vision was used, since the test was devised to determine the light sense of aviators and to conform as closely as possible to their working conditions. The stimulus consisted of a rectangular area subtending a visual angle of approximately 10°, illuminated by a Siemans gas-filled lamp giving 20 cp. when operated at 0.7 amp. The lamp was connected with a three-dial resistance box, graduated to 0.01 ohm. The threshold value of the stimulus was determined by adding resistance to the circuit and the resultant candle-power of the lamp was read from a chart in which cp. was calibrated against current. The cp. of the lamp was then multiplied by 0.53, the coefficient of reflection of the screen on which the light was thrown, and the value of the threshold specified in illumination units. With complete dark adaptation Jones found the maximum sensitivity to be approximately 20° on the temporal side. There was little change in sensitivity from 20°—40°, and slight decrease between 40° and 60°. Great individual differences were found, the most

[1] Abney and Watson state that the two classes could readily be distinguished by viewing a spot of spectrum light oscillating at critical frequency on a white screen at a distance of 1 meter. With 527 mμ (green) of moderate intensity as stimulus, for the observers in Class I the stimulus was seen to change from bright green at the side to dark green as it passed across the fixation point; with less intense light it was seen as bright green at the sides and disappeared entirely at the center. For the observers in Class II, however, there was no change in the brightness of the stimulus as it passed across the fixation point, and a continuous band of green was seen for all intensities above the threshold. With 632 mμ (red) as stimulus, the stimulus was seen brighter at the center than at the sides for observers in both classes at all intensities. Ten observers were examined briefly by this method, eight of whom fell in Class I.

TABLES 20–21
ACHROMATIC THRESHOLDS, DARK ADAPTATION.

Showing the energy values of spectrum lights at the eye required just to arouse the achromatic sensation at near-lying points from center to periphery in the temporal and nasal quadrants of the 180° meridian and the upper and lower quadrants of the 90° meridian.

TABLE 20
ACHROMATIC THRESHOLDS—(DARK-ADAPTED EYE)

Degrees Eccentricity in Field of Vision	Amount of Light Entering Eye (Watts x 10^{-13})							
	Temporal Quadrant—180° Meridian				Nasal Quadrant—180° Meridian			
	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ
0°	0.15116	0.05198	0.04361	0.673	0.15116	0.05198	0.04361	0.673
1°	0.04389	0.04549	0.01288	0.249	0.03326	0.04549	....	0.673
2°	0.03640	0.04332	0.00912	0.206	0.02491	0.03682	0.00738	0.637
4°	0.01294	0.02383	0.00617	0.172	0.01717	0.01733	0.00671	0.292
5°	0.01076	0.01754	0.00537	0.163	0.01258	0.00888	0.00362	0.326
10°	0.00616	0.01105	0.00376	0.172	0.00689	0.00780	0.00208	0.309
13°	0.01016	0.01538	0.00644	0.335	....	....	....	....
15°	B.S.	B.S.	B.S.	B.S.	0.00314	0.00498	0.00114	0.154
19°	0.00943	0.00996	0.00362	0.172	....	....	....	....
20°	0.00544	0.00888	0.00362	0.172	0.00254	0.00520	0.00103	0.112
25°	0.00327	0.00585	0.00168	0.129	0.00254	0.00520	0.00100	0.060
30°	0.00290	0.00455	0.00154	0.043	0.00206	0.00368	0.00094	0.043
40°	0.00254	0.00390	0.00114	0.034	0.00169	0.00412	0.00081	0.051
50°	0.00181	0.00411	0.00128	0.026	0.00290	0.01126	0.00134	0.154
60°	0.00206	0.00542	0.00141	0.033	0.00363	0.01169	0.00174	0.429
70°	0.00290	0.00563	0.00168	0.036	....	....	....	....
80°	0.00314	0.01083	0.00215	0.039	....	....	....	....
90°	....	....	....	0.103	....	....	....	....

TABLE 21

ACHROMATIC THRESHOLDS—(DARK-ADAPTED EYE)

Degrees Eccentricity in Field of Vision	Amount of Light Entering Eye (Watts x 10^{-13})							
	Upper Quadrant—90° Meridian				Lower Quadrant—90° meridian			
	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ
0°	0.15116	0.05198	0.04361	0.673	0.15116	0.05198	0.04361	0.673
1°	0.04317	....	0.01342	0.627	0.03713	0.05198	0.01268	0.283
2°	0.02346	0.04549	....	0.558	0.02648	0.04765	0.00537	0.283
3°	....	....	0.01136	....	....	0.03682	....	....
4°	0.01753	0.01733	0.01127	0.283	0.01391	0.02166	0.00537	0.223
5°	0.01221	0.01949	0.00557	0.223	0.00967	0.01711	0.00363	0.220
10°	0.00460	0.01516	0.00335	0.146	0.00508	0.01538	0.00208	0.163
15°	0.00423	0.01083	0.00362	0.120	0.00460	0.00996	0.00127	0.077
20°	0.00435	0.01083	0.00315	0.137	0.00266	0.00498	0.00114	0.069
25°	0.00339	0.00866	0.00174	0.103	0.00181	0.00455	0.00094	0.042
30°	0.00242	0.00866	0.00255	0.077	0.00181	0.00368	0.00087	0.021
35°	0.00435	0.00866	0.00349	0.094	....	....	....	....
40°	....	....	....	....	0.00169	0.00433	0.00087	0.020
45°	0.00435	0.01083	0.00376	0.103	....	....	....	....
50°	....	....	....	....	0.00206	0.00520	0.00094	0.021
55°	0.00653	0.02383	0.00584	0.120	....	....	....	....
60°	....	....	....	....	0.00327	0.00715	0.00154	0.021
70°	....	....	....	....	0.00363	0.01321	0.00188	0.022
80°	....	....	....	....	....	....	....	0.031

sensitive of his observers having a sensitivity 17 times that of his least sensitive observer. The order of ranking of the observers as to sensitivity was the same, however, for both central and peripheral vision.

In the present investigation the achromatic thresholds were determined under dark adaptation at the same points in the four

FIGURES 39–40. Curves showing the energy values of spectrum lights required just to arouse the achromatic sensation from center to periphery in the 180° and 90° meridians, dark adaptation.

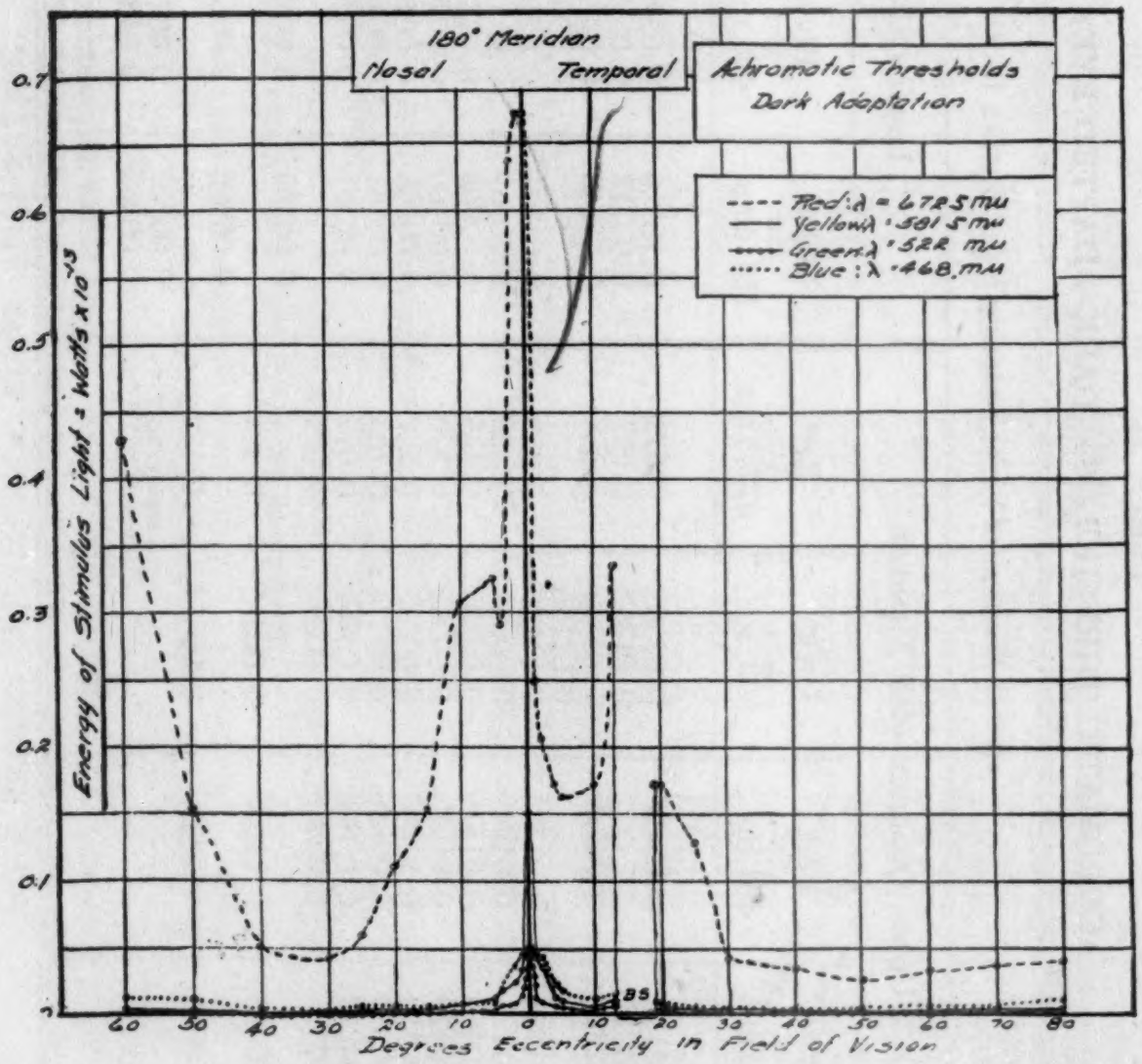


FIG. 39

principal quadrants, upper, lower, nasal and temporal, as were the chromatic thresholds. The values of these thresholds in watts x 10^{-13} are given in Tables 20–21 and are shown in the form of curves in Figs. 39–40. It is seen in these charts that the values

of the red threshold are far in excess of those of the other three colors, particularly for the central and paracentral regions. In order to show the comparative thresholds for the four colors, it was necessary therefore to use a scale of representation which obscured the changes in the threshold values from center to periphery in case of yellow, green and blue. In order to show these changes, the threshold curves for yellow, green and blue are shown again in Figs. 41–42, plotted on a scale of ordinates five times as large as was used in the charts for the four colors.

The data plotted in the form of sensitivity curves are given in Fig. 43. As before, sensitivity is represented as the reciprocal of the threshold value in watts. A comparison of the threshold and the sensitivity curves shows that the central and paracentral relationships of achromatic sensitivity are brought out more clearly by the threshold curves; the peripheral relationships by the sensitivity curves. This is the reverse of what was found in the representation of chromatic sensitivity.

The following points of interest in these results may be noted:

1. *The achromatic thresholds for all wave-lengths are much higher and the sensitivity much lower at the center than at any other point in the field of vision.* That is, the achromatic sensitivity of the retina when dark-adapted is much lower at the fovea than at any other point.

2. *The sensitivity increases rapidly within the first* 5° *from the center.* There is an average percentage increase in sensitivity for the four meridional quadrants investigated of 1,254, 901, 263 and 221 per cent for yellow, green, blue and red, respectively. The percentage increase in each quadrant for each of the colors is given in the following table:

PERCENTAGE INCREASE IN SENSITIVITY FROM 0° TO 5°

Stimulus	Temporal	Nasal	Upper	Lower
Red (672.5 mμ).....	336	114	214	221
Yellow (581.5 mμ).....	1307	1104	1140	1465
Green (522 mμ).....	713	1105	683	1104
Blue (468 mμ).....	196	486	167	204

Beyond 5° the sensitivity continues to increase, but more gradually, reaching a maximum value between 30° and 50°.

From this point to the periphery it decreases somewhat, although never reaching the value found for the center of the field. At the edge of the blind spot in the temporal quadrant there is a relative loss of sensitivity for approximately 3° on the nasal side before the point of complete insensitivity is reached. On the

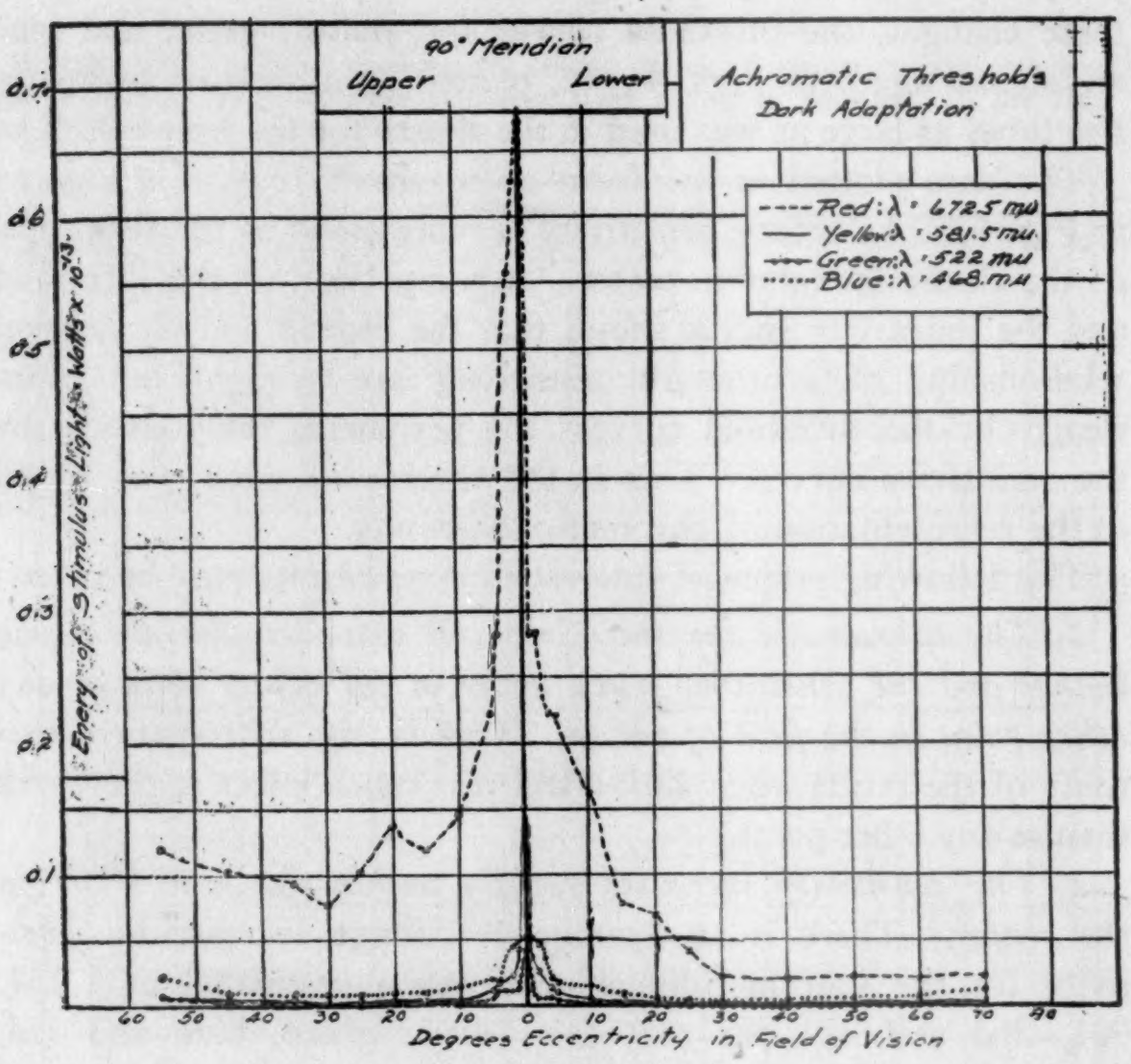


FIG. 40

temporal side, however, the demarcation between complete insensitivity and the sensitivity of the adjacent field is sharp, with no apparent gradations. Ophthalmoscopic examination of the observer's eye shows a conus or choroidal crescent on the temporal side of the disc corresponding to the area of gradual loss of sensitivity on the nasal side of the blind spot. Although the choroid is rarefied in this area, portions of it remain as indicated by the pigmentation present. A partial rather than a complete

loss of sensitivity might be expected, therefore, within this area. The writer hopes in the near future to obtain further data as to

FIGURES 41–42. Curves showing on an amplified scale the energy values of yellow, green and blue spectrum light required just to arouse the achromatic sensation from center to periphery of the field in the 180° and 90° meridians, dark adaptation.

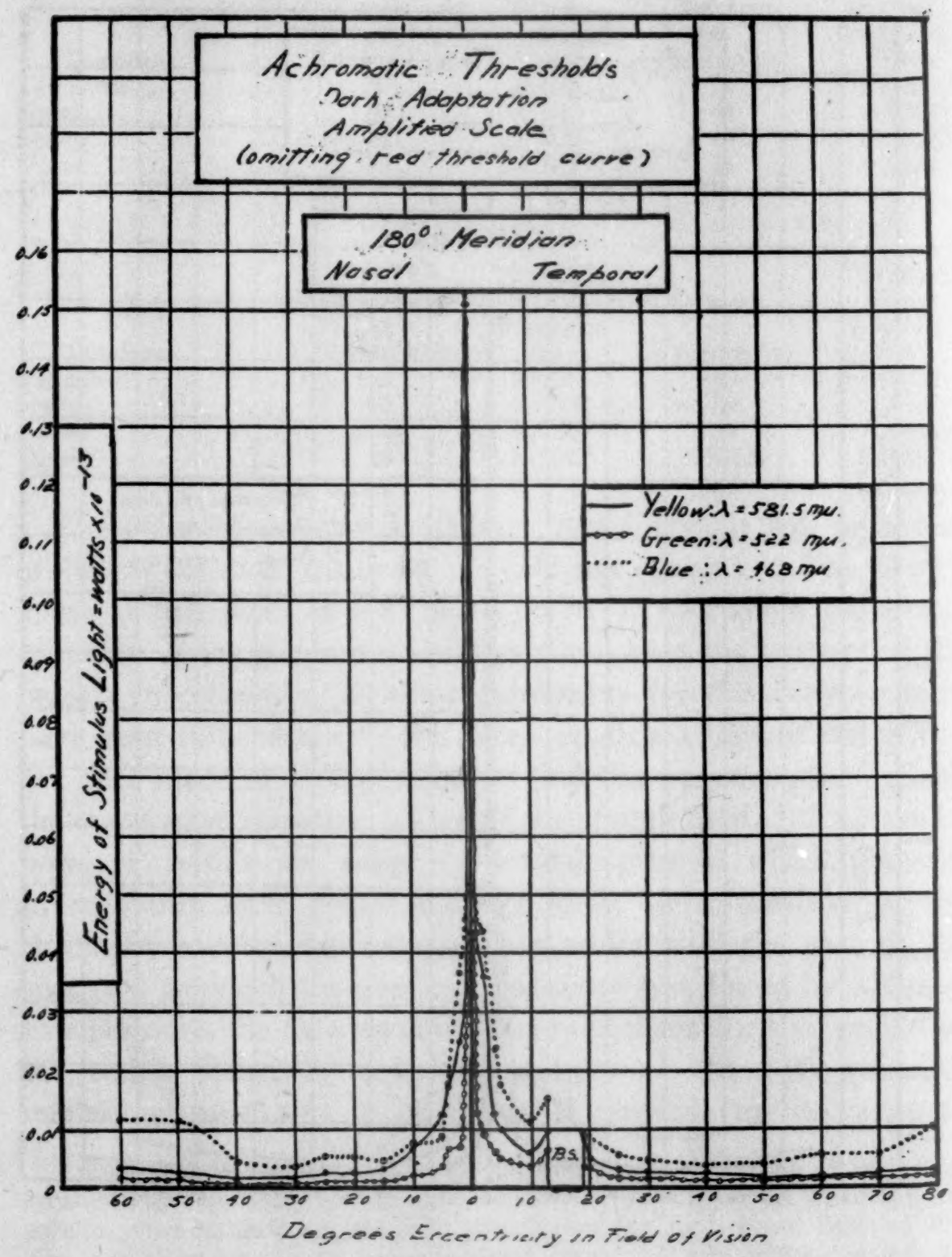


FIG. 41

the relation of changes in sensitivity immediately about the blind spot to ophthalmoscopic findings of this nature.

3. *The maximum achromatic sensitivity to the stimuli employed falls between* 40° *and* 50° *in the temporal field, between* 30° *and* 40° *in the lower and nasal field, and between* 25° *and* 35°

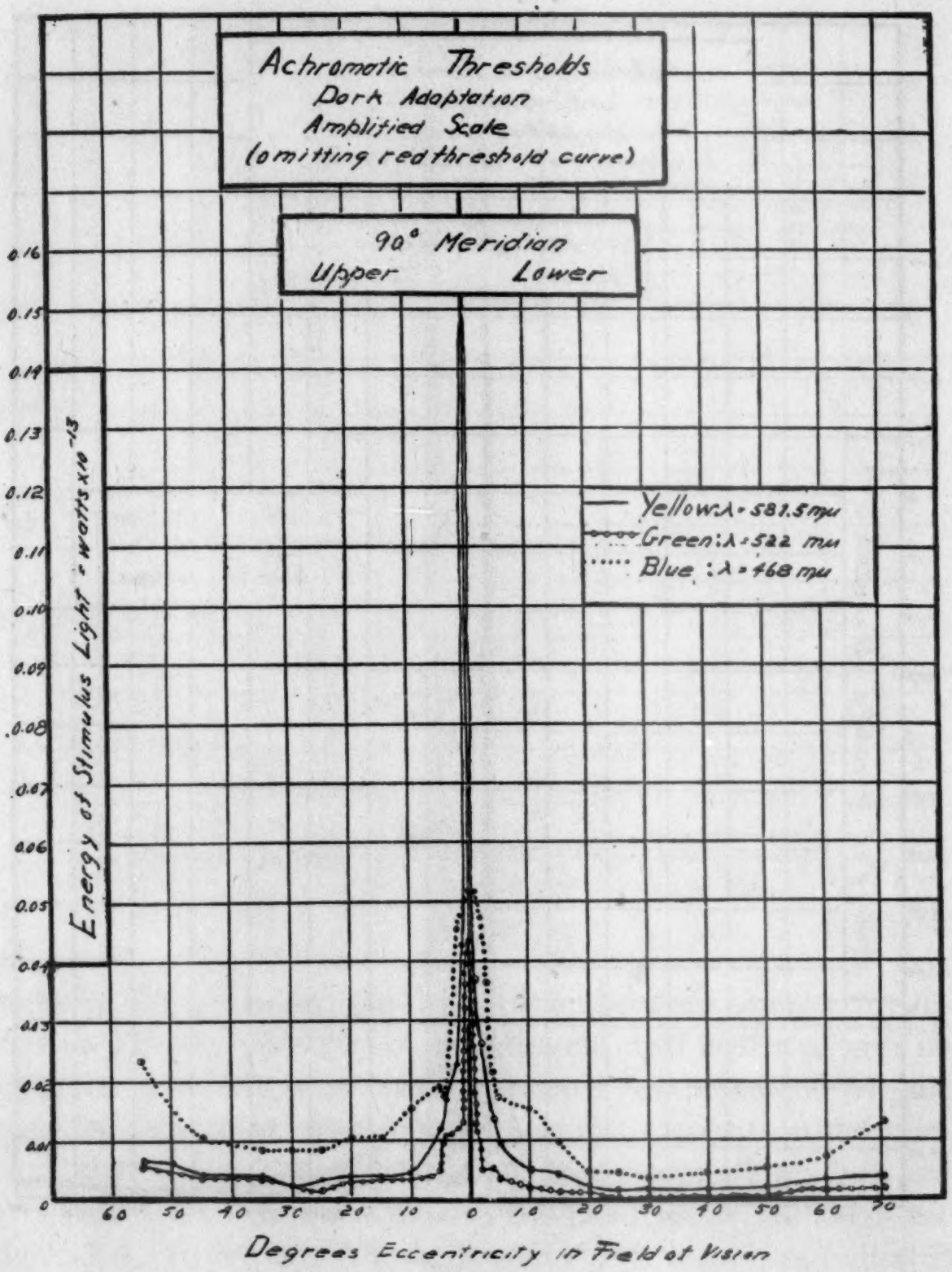


FIG. 42

in the upper field. The position of the maximum for each stimulus and the threshold values at each point of maximum sensitivity are as follows:

	Red (672.5 mμ)		Yellow (581.5 mμ)	
Quadrant	Degrees of Eccentricity	Threshold Values (watts x 10^{-13})	Degrees of Eccentricity	Threshold Values (watts x 10^{-13})
Temporal	50	0.026	50	0.0018
Nasal	30	0.043	40	0.0017
Lower	40	0.020	40	0.0017
Upper	30	0.077	30	0.0024

	Green (522 mμ)		Blue (468 mμ)	
Quadrant	Degrees of Eccentricity	Threshold Values (watts x 10^{-13})	Degrees of Eccentricity	Threshold Values (watts x 10^{-13})
Temporal	40	0.0011	40	0.0039
Nasal	40	0.0008	30	0.0037
Lower	30–40	0.0009	30	0.0037
Upper	25	0.0017	25–35	0.0087

The point of greatest sensitivity was found, it will be noted, at 40° in the nasal quadrant for 522 mμ (green).[1] The energy value at this point is 0.81 watts x 10^{-16}. Although the determination of the minimum visible has not been the purpose of the present investigation, all the requirements for this determination have been fully met with the exception that a minute search has not been made of the spectrum to find the wave-length to which the eye is most sensitive. One of the stimuli used, 522 mμ, falls, however, within the range of wave-lengths to which previous investigators have found the eye to be most sensitive at the threshold level of intensity, and coincides with the part of the spectrum to which the greatest sensitivity was found by Monroe. Furthermore, the determination has been made for that region of the retina found by a careful survey of the four principal meridional quadrants to be the most sensitive to the range of

[1] This was 10°–20° nearer to the periphery than the point of maximum sensitivity obtained by Jones. The conditions used, however, are not comparable, since he used a white light stimulus subtending a visual angle of 10°. The size alone of this stimulus rendered impossible any minute search for the point of greatest sensitivity.

wave-lengths selected. There still remain, it is true, other areas of the retina to be examined. The present survey is far more extensive, however, than any that has previously been made, and the results would seem, therefore, to merit consideration at least along with the others purporting to represent the minimum visible. For convenience of comparison a brief summary of the values previously obtained, as given by Monroe, will be found in the following table:

Wien	40.00 w x 10^{-16}	Reeves	1.95 w x 10^{-16}
Drude-Coblentz	1.70 " "	von Kries	0.20 " "
Ives	3.80 " "	Boswell	2.37 " "
Russell	0.77 " "	Monroe (522 mμ) av.	2.30 " "
Buisson	1.25 " "	smallest value	0.64 " "

Present Study (522 mμ)

Central vision	43.61 w x 10^{-16}
Peripheral vision, smallest value	0.81 " "

The value of the minimum visible for central vision given in the present study is higher, it will be noted, than that obtained by Monroe, the only one of the above investigators who worked under even approximately similar conditions of experimentation. The stimulus used by Monroe, however, subtended a visual angle of 2°, that of the writer but 1°. Since the threshold value for green decreases nearly 75 per cent within 1° of the fixation point this difference in size of the stimulus might very easily account for the differences obtained, aside from the individual variations which are known to exist.

4. *The curves showing the variation in achromatic sensitivity from center to periphery in a given meridian are quite different in character for the different wave-lengths.* Viewed as topographical outlines of the levels of sensitivity, for the different wave-lengths in any meridional quadrant, the curve for red forms in effect a broad low plateau showing little change in level from center to periphery; the curves for blue and yellow rise to higher and more rounded levels; while the curve for green is highest throughout in all quadrants and culminates in a sharp peak with steeply sloping sides in all quadrants but one.

5. *Not only is there a great difference in the relative sensitivity to wave-length at a given point but this difference changes*

from point to point in the same quadrant. In order to bring out these differences more clearly the same type of comparison was made of achromatic sensitivity to the different stimuli used as has already been made for chromatic sensitivity, light and dark adaptation. This comparison is given in Table 22 and the series

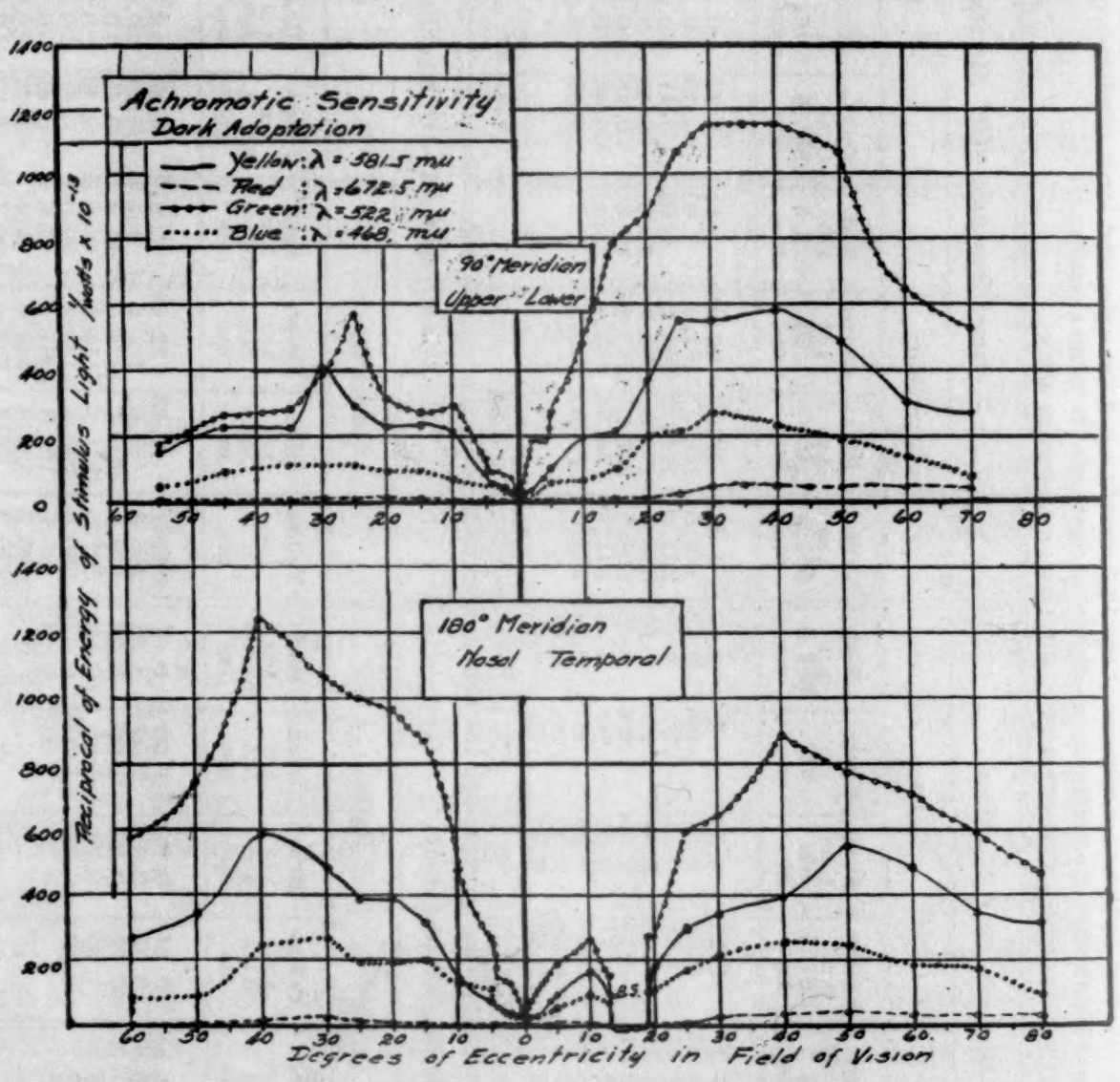

Achromatic Sensitivity
Dark Adaptation
Yellow: λ = 581.5 mμ
Red : λ = 672.5 mμ
Green: λ = 522 mμ
Blue : λ = 468 mμ
90° Meridian
Upper Lower
180° Meridian
Nasal Temporal
Reciprocal of Energy of Stimulus Light Watts x 10⁻¹⁵
Degrees of Eccentricity in Field of Vision

FIGURE 43. Curves showing the achromatic sensitivity to spectrum lights from center to periphery of the field in the 180° and 90° meridians, dark adaptation.

of curves in column 3, Fig. 12. These curves are plotted in the form of four-point sensitivity curves. They show the relative sensitivity to the different stimuli at intervals of 10° in the temporal 180° quadrant selected as typical, when the maximum sensitivity at each point is represented as unity. The highest sensitivity in every case is to green and the lowest to red. The order of sensitivity from highest to lowest at the center is green, blue,

TABLE 22.

ACHROMATIC SENSITIVITY, DARK ADAPTATION.

Showing the achromatic sensitivity to the four spectrum lights expressed as the reciprocal of the energy of the stimulus required just to arouse the achromatic sensation at the points selected in the temporal and nasal quadrants of the 180° meridian and the upper and lower quadrants of the 90°.meridian. Included also are ratios of sensitivity to the different colors when the maximum sensitivity at each point is taken as unity.

ACHROMATIC SENSITIVITY—(DARK-ADAPTED EYE)

Degrees Eccentricity in Field of Vision	Temporal Quadrant—180° Meridian								Nasal Quadrant—180° Meridian							
	Sensitivity				Ratio				Sensitivity				Ratio			
	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ
0°	6.613	19.23	22.93	1.15	0.29	0.84	1.00	0.07	6.613	19.23	22.93	1.51	0.29	0.84	1.00	0.07
10°	162.153	90.57	266.16	5.81	0.61	0.34	1.00	0.02	145.00	128.2	481.0	3.23	0.30	0.27	1.00	0.07
20°	183.78	112.61	276.09	5.81	0.66	0.41	1.00	0.02	393.80	192.3	968.9	8.92	0.41	0.20	1.00	0.01
30°	344.58	219.87	648.08	23.25	0.53	0.34	1.00	0.03	486.6	271.5	1064.7	23.2	0.46	0.26	1.00	0.02
40°	393.85	256.54	877.19	29.41	0.45	0.29	1.00	0.03	590.6	243.0	1242.2	19.6	0.48	0.20	1.00	0.02
50°	551.57	243.01	778.81	38.46	0.71	0.31	1.00	0.05	344.5	88.8	745.7	6.4	0.46	0.12	1.00	0.009
60°	486.61	184.67	710.22	30.30	0.68	0.26	1.00	0.04	275.7	85.5	573.3	2.3	0.48	0.15	1.00	0.004
70°	344.58	177.58	596.30	27.77	0.58	0.30	1.00	0.05	....	....	....	....	....	....	....	....
80°	318.06	92.33	465.98	25.64	0.68	0.20	1.00	0.06	....	....	....	....	....	....	....	....
90°	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....

	Upper Quadrant—90° Meridian								Lower Quadrant—90° Meridian							
	Sensitivity				Ratio				Sensitivity				Ratio			
	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ
0°	6.613	19.23	22.93	1.51	0.29	0.84	1.00	0.07	6.613	19.23	22.93	1.51	0.29	0.84	1.00	0.07
10°	217.6	65.9	298.9	6.8	0.93	0.22	1.00	0.02	196.8	65.0	481.0	6.1	0.41	0.13	1.00	0.01
20°	229.7	92.3	317.1	7.2	0.72	0.29	1.00	0.02	375.9	200.7	877.1	14.4	0.43	0.23	1.00	0.02
30°	413.5	115.4	392.3	12.9	1.00	0.28	0.95	0.03	551.5	271.5	1146.6	47.6	0.48	0.24	1.00	0.04
40°	229.7*	92.3*	226.1*	9.7*	0.89*	0.35*	1.00*	0.04*	590.6	230.8	1146.6	50.0	0.51	0.21	1.00	0.04
50°	153.1†	41.9†	171.3†	8.3†	†	0.25†	1.00†	0.05†	486.6	192.3	1064.2	47.6	0.45	0.18	1.00	0.04
60°	....	....	....	....	....	....	....	....	306.2	139.8	648.0	45.4	0.47	0.22	1.00	0.07
70°	....	....	....	....	....	....	....	....	275.7	75.7	532.4	32.2	0.52	0.14	1.00	0.06

*—Sensitivity at 45° Eccentricity. †—Sensitivity at 55° Eccentricity.

yellow, red. At every other point the order is green, yellow, blue, red. A comparison of the series of curves given in the three columns of Fig. 12 shows that there is more uniformity in the order of sensitivity to the different stimuli from point to point in the same quadrant in case of achromatic sensitivity, dark adaptation, than in case of chromatic sensitivity, either dark or light adaptation.

In connection with the question of selectiveness of sensitivity to wave-length at threshold intensities, a comparison of results is possible only with those obtained by Monroe for central vision. The threshold values obtained for central vision in each case are as follows:

	Threshold Values (watts x 10^{-13})		
		Monroe (20 observers)	
Wave-length	Wentworth	Average	Range
Red (672 mμ)	0.673		
Red (655 mμ)		0.626	1.209 –0.0186
Yellow (581 mμ)	0.151	0.0279	0.049 –0.012
Green (522 mμ)	0.043	0.0019	0.0034–0.0012
Blue (468 mμ)	0.051		
Blue (463 mμ)		0.0151	0.029 –0.006

It will be noted that the order of ranking of the colors as to sensitivity is the same for both investigations. The greatest difference is in the magnitude of the threshold values for yellow and green. Since the threshold values for both of these stimuli are lowered from 60–75 per cent within 1° of the center of the field, the disparity may well be accounted for on the same grounds as that found in the determinations of the minimum visible, namely, size of stimulus.

In concluding this section, it may be of interest to point out that, in so far as there is lower sensitivity at the fovea than in the parafoveal region, the writer belongs to Class I of the observers of Abney and Watson. She differs from these observers in that there was a lower sensitivity at the fovea to red as well as to the other colors and in that a photochromatic interval, though small, was found at the center of the field for all the stimuli employed.

III. *The Photochromatic Interval.*

By photochromatic interval is meant the colorless interval between the achromatic and chromatic thresholds for any given chromatic stimulus. It is possible, therefore, to express this interval on the stimulus scale in absolute terms,—terms which admit of numerical comparison not only from wave-length to wave-length but also from point to point in the field. The latter comparison is of particular interest since to the writer's knowledge the photochromatic interval has never before been made a subject even for consideration for the paracentral and peripheral portions of the field. Indeed, for central vision there has been but one determination of the absolute value of the photochromatic interval, that of Monroe in 1925. Previous to this, as she has pointed out, the interval had been discussed only in most general terms. Tschermak (97), Fick (98), von Kries (99), Hering (100), and others noted its existence and that it varied under different conditions. Charpentier (101) alone had attempted to make a numerical statement of its value. Using as stimulus the light from a solar spectrum focussed on ground glass, he reduced the intensity to the threshold value by means of a diaphragm and expressed the relation of the achromatic to the chromatic threshold in terms of the square of the diameter of aperture used. No measurements were made, either photometric or radiometric, and the wave-length was not specified. His ratios were as follows:

Rouge extreme	3.6
Orangé	5.5
Jaune	9.6
Vert moyen	196.0
Bleu franc, région moyenne	635.0

In 1892 Abney and Festing (102) determined the achromatic and chromatic thresholds throughout the spectrum. They did not, however, attempt to assign any values, either relative or absolute, to the photochromatic interval as such, nor can these values be calculated from their data because of the indefinite specification of their stimulus.

Monroe (**81**) determined the value in radiometric units of the achromatic and chromatic threshold at seven points in the spectrum for twenty observers. From these data she calculated the photochromatic intervals as follows:

Wave-length	Value of Interval (Watts x 10^{-13})	Ratio (Yellow = 1)
655 mμ	1.1530	.01
616 mμ	5.4897	.06
580 mμ	95.6720	1.000
553 mμ	0.8533	.009
522 mμ	1.4295	.02
489 mμ	6.4219	.07
463 mμ	8.1043	.08

She obtained a curve for these values sustaining roughly, as might be expected, an inverse relation to her curve of chromatic sensitivity. That is, the smallest photochromatic interval and greatest chromatic sensitivity were in the yellow-green; the greatest interval and least sensitivity, in the yellow.

In the present study the photochromatic interval was determined at near-lying points from center to periphery of the retina in the four principal meridional quadrants,—upper, lower, temporal, and nasal. The points at which the determinations were made and the values obtained are given in Tables 23–24.

For convenience of comparison and graphic representation, Table 25 has been compiled to show for the different stimuli at each point the relative values of the interval when the maximum value at that point is taken as unity. At all points more than 30° from the center, however, one or more of these stimuli remains colorless whatever its intensity; that is, the photochromatic interval for it approaches infinity.

Graphic representations of these data are given in Figs. 44 and 45. In these representations the photochromatic interval is shown in black, the remainder of the figure in white. Degrees of eccentricity are plotted along the abscissa and energy values (watts x 10^{-13}) along the ordinate. Because of the great range in the values of the photochromatic interval from center to periphery, a constant scale of ordinates could not be used without masking the relatively small variations in the interval near the center. To obviate this, the plan was adopted of representing all

TABLES 23–24.
PHOTOCHROMATIC INTERVAL, DARK ADAPTATION.

Showing the energy value of the photochromatic interval for spectrum lights at near-lying points from center to periphery in the temporal and nasal quadrants of the 180° meridian and the upper and lower quadrants of the 90° meridian.

TABLE 23

Degrees Eccentricity in Field of Vision	Difference in Amount of Light Entering Eye between the Achromatic and Chromatic Thresholds (Watts x 10^{-13})							
	Temporal Quadrant—180° Meridian				Nasal Quadrant—180° Meridian			
	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ
0°	0.1270	0.0650	0.0436	0.0393	0.1270	0.0650	0.0436	0.0393
1°	0.2826	0.0715	....	0.9534	0.2448	0.0758	....	0.056
2°	0.2538	0.1083	0.0915	1.0212	0.2653	0.0910	0.0865	0.092
4°	0.3257	0.2570	0.1011	1.5530	0.2972	0.3098	0.0872	0.601
5°	0.5456	0.1818	0.1087	1.9452	1.2088	0.1969	0.0970	0.884
10°	1.8924	0.1362	0.1773	3.1925	1.3837	0.1915	0.1187	1.013
13°	1.9972	0.3117	0.1949	2.840	....	....	....	....
15°	B.S.*	B.S.*	B.S.*	B.S.*	1.8471	0.8896	0.2203	1.168
19°	2.7236	0.3171	6.1016	1.836	....	....	....	....
20°	2.7276	0.3507	6.1016	1.836	1.9318	1.0800	0.9919	2.462
25°	4.1083	0.7804	5.9022	2.866	1.8961	1.2359	3.4283	2.858
30°	5.8985	1.0016	7.8477	27.291	6.3588	1.8894	4.7759	3.647
40°	10.8207	1.8177	....	86.352	18.7062	....	11.4716	8.531
50°	18.0530	....	....	86.361	24.1831	....	....	65.927
60°	31.5727	....	....	132.440	33.8568	....	....	107.704
70°	37.7756	....	....	188.047	....	....	....	....
80°	....	....	....	268.024	....	....	....	....
90°	....	....	....	288.407	....	....	....	....

*Blind spot

TABLE 24

Degrees Eccentricity in Field of Vision	Difference in Amount of Light Entering Eye between the Achromatic and Chromatic Thresholds (Watts x 10^{-13})							
	Upper Quadrant—90°Meridian				Lower Quadrant—90° Meridian			
	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ
0°	0.1270	0.0650	0.0436	0.0393	0.1270	0.0650	0.0436	0.0393
1°	0.2349	....	0.0872	0.2226	0.2410	0.0650	0.0879	0.6953
2°	0.3030	0.0975	....	0.0599	0.3000	0.0736	0.1019	0.9957
3°	....	....	0.1037	....	....	0.1062	....	....
4°	0.2848	0.2253	0.1095	1.2446	0.3064	0.2989	0.1154	1.219
5°	1.1971	0.1971	0.1957	1.5964	0.5103	0.2016	0.1440	1.445
10°	1.3861	0.1061	0.3790	5.3766	0.7323	0.1839	0.1925	1.279
15°	3.0311	0.0997	0.7210	2.7979	1.1080	0.3961	1.6386	2.609
20°	23.5770	0.2318	3.2171	2.701	1.0033	0.9003	2.8033	2.198
25°	32.0431	0.2924	6.2511	7.363	1.6116	0.7274	3.4274	2.378
30°	37.1231	0.3574	9.3833	61.628	2.1145	2.1666	4.9168	3.609
35°	54.2932	1.0310*	....	68.476	....	....	....	....
40°	....	....	....	....	2.8764	....	10.1968	4.546
45°	69.6513	....	....	111.403	....	....	....	....
50°	....	....	....	....	4.8230	....	....	4.605
55°	77.8724	....	....	171.520	....	....	....	....
60°	....	....	....	....	28.7539	....	....	30.616
70°	....	....	....	....	35.0064	....	....	37.567
80°	....	....	....	....	....	....	....	264.123

*32° out on meridian

values above 5 watts x 10^{-13} on a scale minified in the relation of 1:20. This minification is made evident in the charts by the horizontal lines which are drawn at intervals of 5 watts x 10^{-13}. By this method of plotting the intervals for green and blue and in nearly all cases for red and yellow within 30° on either side of the center, the most interesting and important region of the field, are represented without distortion. The values for red and yellow at points beyond 30° in the insensitive periphery are, however, reduced. Other methods of plotting could, of course, have been employed: (a) A logarithmic scale of ordinates could have been used, or (b) the intervals in the central and paracentral portions of the field could have been shown in an inset drawn to an amplified scale, as was done in representing the values of the chromatic thresholds in an earlier section of the paper.

The variations in the relative values of the photochromatic interval from center to periphery of the field have been shown also in the form of four-point curves. In drawing these curves the highest value of interval is taken as unity. The relationships are shown at 2°, 4°, 5°, 10°, 15°, 20°, and 30° from the center of the field in the temporal, nasal, upper and lower quadrants (Fig. 46).

The following points may be noted:

(1) *In general the photochromatic interval may be said to increase progressively from center to periphery.* This increase, however, is subject to fluctuations of considerable extent, particularly for red, due chiefly to the great irregularities in the values of the chromatic thresholds from point to point. Of interest in this connection, too, are the small peaks of increase in the graphs for blue occurring at 4° from the center and the decrease in the intervals for yellow at the same point. It will be remembered that the chromatic sensitivity curves showed a sudden decrease in sensitivity to blue at this point and a corresponding increase in sensitivity to yellow.

(2) *A marked difference is seen to occur in the rate of increase in the value of the interval from center to periphery for the different wave-lengths.* The interval for red, which is extremely small at the center, increases abruptly within 1° or 2°, changing

FIGURES 44–45. Charts showing the photochromatic interval for spectrum lights from center to periphery of the field for the 180° and 90° meridians, dark adaptation.

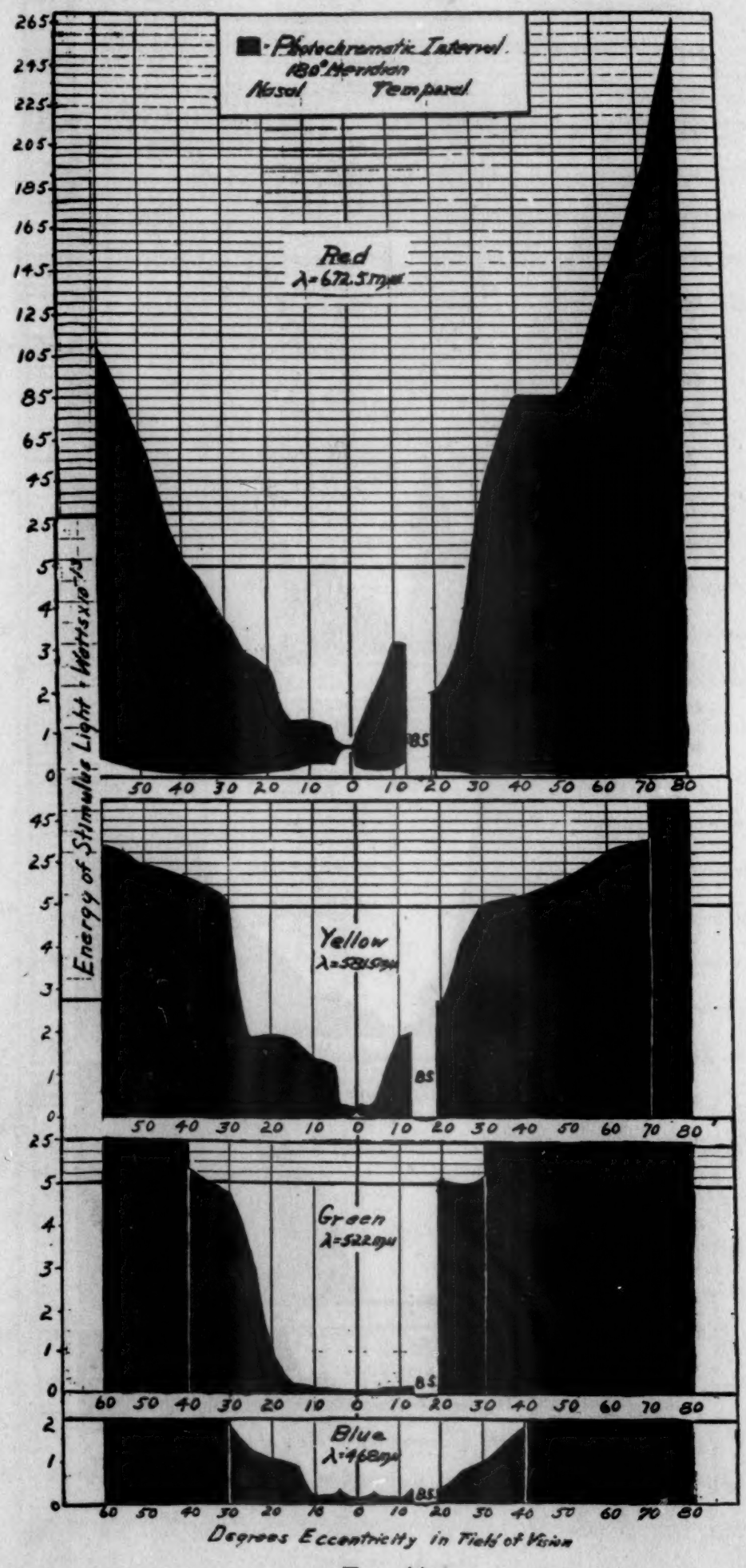


FIG. 44

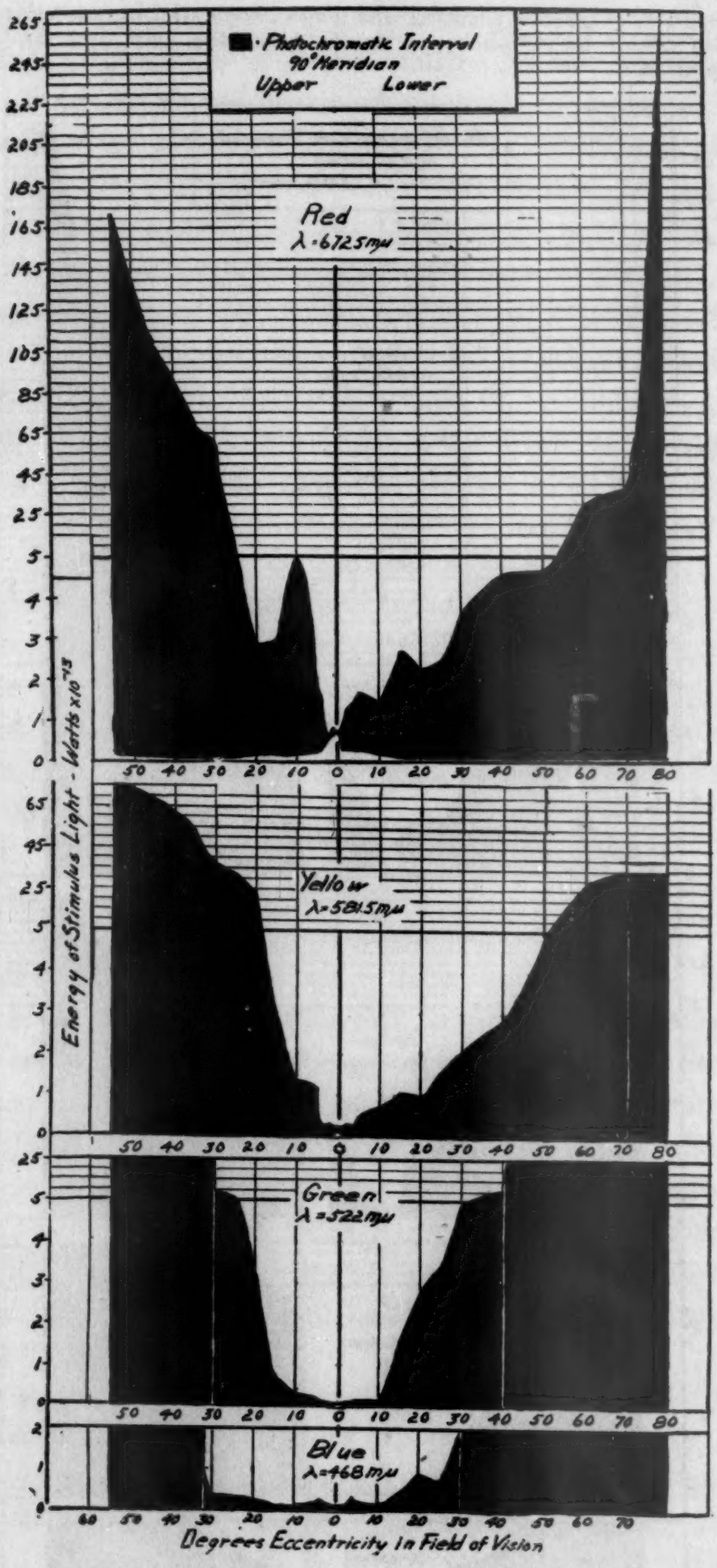
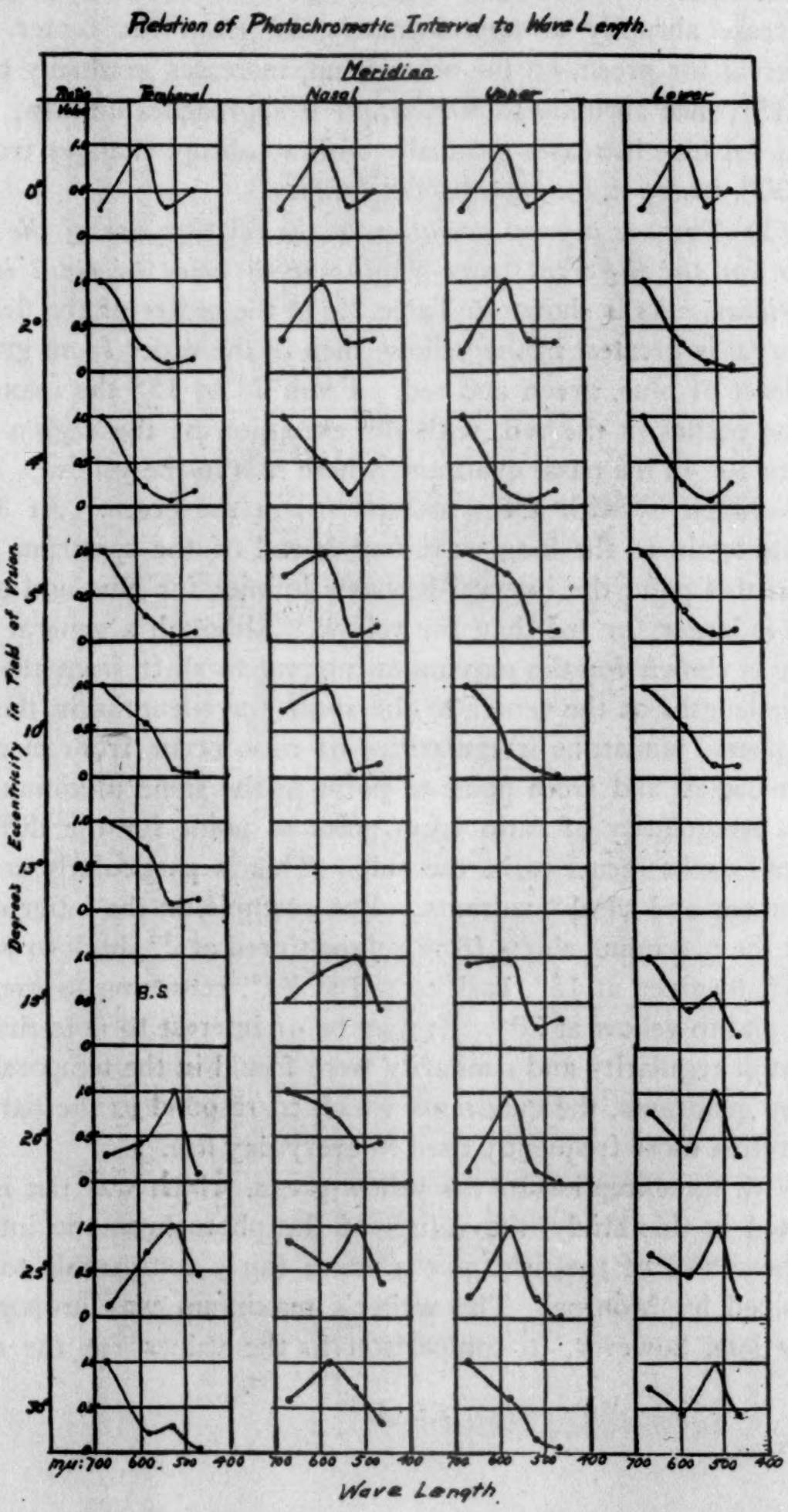

Photochromatic Interval
90° Meridian
Upper Lower
Red
λ-6725mμ
Yellow
λ-5815mμ
Green
λ-522mμ
Blue
λ-468mμ
Energy of Stimulus Light - Watts x10⁻¹³
Degrees Eccentricity In Field of Vision

FIG. 45

FIGURE 46. Four-point curves showing a comparison of the values of the photochromatic interval for spectrum lights at selected points in the 180° and 90° meridians, when the maximum value of the interval at each point is taken as unity.



from a minimum to a maximum value in relation to the other wave-lengths. The interval for yellow which is of maximum value relative to the other wave-lengths at the center is seen to increase abruptly at approximately 5° from the center. The interval for green, on the other hand, increases gradually to 10° or 15°, then abruptly to 30°, where it approaches infinity; while that for blue increases gradually with no abrupt changes from 0° to 30°, where it, too, approaches infinity.

(3) *There is a great variation in the relative size of the intervals for the different wave-lengths from point to point in any meridian.* As is shown in Table 25, at the center of the field the interval is greatest in the yellow, then in the order from greatest to least of blue, green and red. From 2° to 15° the maximum value occurs in the red, with the exception of the region from 5° to 10° in the nasal quadrant, where it is in the yellow. From 15°–30° it is, with a few exceptions, in the green. At 30° it shifts again to the long wave-length end of the spectrum. Beyond this point the interval becomes infinite for blue and green, and is larger for red than for yellow. Although a general tendency is shown for the maximum interval to shift from the long wave-lengths at the center to the short wave-lengths in the mid periphery, numerous irregularities of ratio occur from meridian to meridian and from point to point in the same meridian. In fact, irregularity of ratio from point to point for the different wave-lengths seems to be the rule. This is particularly true in the upper and nasal quadrants. For example, in the latter quadrant the maximum shifts from yellow to red at 2°, back to yellow at 5°, to green at 15°, back to red at 20°, returning to green at 25° and to yellow at 30°. It may be of interest to note that the greatest regularity and similarity were found in the temporal and lower quadrants, the quadrants which correspond to the parts of the retina most frequently used in every day life.

With the exception of the yellow-green, which was not investigated in this study, the values of the photochromatic interval at the center of the field give a curve fairly comparable to that obtained by Monroe. The writer's maximum was proportionately less, however, in comparison to the values for the other

TABLE 25.

COMPARATIVE VALUES OF PHOTOCHROMATIC INTERVAL.

Showing a comparison of the values of the photochromatic interval for different spectrum lights at near-lying points from center to periphery, when the maximum value of the interval at each point is taken as unity.

Degrees Eccentricity in Field of Vision	180° Meridian								90° Meridian							
	Temporal				Nasal				Upper				Lower			
	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ	Yellow λ= 581.5 mμ	Blue λ= 468 mμ	Green λ= 522 mμ	Red λ= 672.5 mμ
0°	1.00	0.51	0.34	0.30	1.00	0.51	0.34	0.30	1.00	0.51	0.34	0.30	1.00	0.51	0.34	0.30
2°	0.25	0.11	0.09	1.00	1.00	0.34	0.32	0.35	1.00	0.32	0.32	0.20	0.30	0.07	0.10	1.00
4°	0.21	0.17	0.06	1.00	0.50	0.52	0.15	1.00	0.23	0.18	0.08	1.00	0.25	0.25	0.09	1.00
5°	0.28	0.09	0.06	1.00	1.00	0.17	0.08	0.73	0.75	0.12	0.12	1.00	0.35	0.14	0.10	1.00
10°	0.59	0.04	0.06	1.00	1.00	0.14	0.09	0.73	0.26	0.02	7	1.00	0.57	0.14	0.15	1.00
13°	0.70	0.11	0.07	1.00	....	....	....	....	....	....	....	....	....	....	....	....
15°	....	....	....	....	0.84	0.41	1.00	0.53	1.00	0.33	0.24	0.92	0.42	0.15	0.63	1.00
19°	0.44	0.51	1.00	0.30	....	....	....	....	....	....	....	....	....	....	....	....
20°	0.44	0.06	1.00	0.30	0.79	0.44	0.40	1.00	1.00	0.01	0.14	0.11	0.36	0.32	1.00	0.79
25°	0.70	0.49	1.00	0.13	0.55	0.36	1.00	0.84	1.00	0.01	0.20	0.23	0.47	0.21	1.00	0.70
30°	0.22	0.03	0.29	1.00	1.00	0.30	0.75	0.57	0.60	0.06	0.15	1.00	0.43	0.44	1.00	0.73
35°	....	....	....	....	....	....	....	....	0.79	....	....	1.00	....	....	....	....
40°	0.13	0.02	....	1.00	1.00	....	0.55	0.46	....	....	....	....	0.28	....	1.00	0.45
45°	....	....	....	....	....	....	....	....	0.62	....	....	1.00	....	....	....	....
50°	0.20	....	....	1.00	0.36	....	....	1.00	....	....	....	....	0.100	....	....	0.96
55°	....	....	....	....	....	....	....	....	0.46	....	....	1.00	....	....	....	....
60°	0.23	....	....	1.00	0.31	....	....	1.00	....	....	....	....	0.94	....	....	1.00
70°	0.20	....	....	1.00	....	....	....	....	....	....	....	....	0.93	....	....	1.00
80°	....	....	....	1.00	....	....	....	....	....	....	....	....	....	....	....	1.00
90°	....	....	....	1.00	....	....	....	....	....	....	....	....	....	....	....	....

wave-lengths, due apparently to a much greater sensitivity in the yellow than was obtained by the majority of Monroe's observers.

C. The Effect of State of Adaptation of the Eye on Chromatic Sensitivity, Central and Peripheral.

That the state of general adaptation of the retina is a factor which affects the eye's powers of response has for a long time been recognized, and careful laboratory workers have in recent years not only controlled and specified the intensity of the illumination under which their work was done, but have provided more or less adequate preliminary periods during which the eye became adapted to the intensity of light that was employed. It is surprising, therefore, to find that very few studies have been made which were planned to show directly the effect of this factor in case of the various types of visual response. The obvious requirements of such a study are (a) two or more intensities of illumination to which the eye is to be adapted for the required length of time; and (b) stimuli to arouse the response under investigation which are completely independent of the illuminations used to produce the adaptation.

Among the few studies on the various types of response which have satisfied these requirements more or less completely, the following may be mentioned:

Nutting (103), in 1916, determined the threshold for white light in ml. immediately after sensitizing the eye by exposure to a surface of known brightness. Twelve brightnesses were used ranging from .00000071–2000 ml. The sensitizing field was 60 cm. square and was viewed at a distance of 35 cm. The visual angle subtended by this field was approximately 82°. After the eye had been sensitized (length of sensitizing period not stated), the illumination of the field was cut off and the brightness determined which made a small square at the center of vision just visible. Nutting's results show that "the curve [representing the variation of the threshold with variation of the brightness of the sensitizing field] is a straight line except at the ends and with a very slight dip in the region of ordinary

brightnesses indicating that there the retina is a little more sensitive than normal." At the lowest intensity the threshold value was .00000071 ml.; at the highest 3.980 ml. The ratio between these two values is 1:5,605,634.

Nutting's experiments, it scarcely need be pointed out, show the effect of a somewhat extensive local preexposure rather than of a complete adaptation of the whole retina.

In 1920 Ferree, Rand and Buckley (104) published the results of a determination of the minimum illumination in meter-candles required just to discriminate an acuity object (detail to be discriminated, 1 min. visual angle) when the eye was completely adapted to an illumination of 80 ft.-c. and when it was dark adapted. Six observers were used. The difference in the amount of light required to discriminate the test-object under the two conditions of adaptation ranged for the different observers from 0.20–1.07 m.c., average 0.65 m.c., the percentage difference, from 57–195, average 123.

In both of the above studies the threshold values for the light-adapted eye were determined in the dark immediately after the sensitizing light had been cut off. In the next two studies and in the work of the writer, in all of which spectrum light was used as stimulus, the eye's response was obtained under the illumination to which it had been adapted.

In 1928 Sloan (82) investigated the eye's selectiveness of achromatic response to wave-length by the equality of brightness method with the eye adapted to 12.5 ft.-c. of daylight illumination and with the eye dark-adapted. The results were represented in the form of visibility curves. The data for these curves were obtained by taking the reciprocals of the energies required in the different parts of the spectrum to give equal achromatic responses. Two sizes of photometric field were used, 57′ and 4°49′, and twelve levels of intensity ranging from 75–.001 m.c. She found particularly for low and medium intensities that the selectiveness of the achromatic response to wave-length was different for the two states of adaptation. For example, at medium intensities (2–10 m.c.) for the extrafoveal size of field there was an increase in relative achromatic sensitivity with light adaptation of 57 per

cent at 619 mμ and 124 per cent at 643 mμ. At low intensities the differences were very much greater. At .01 m.c. with light adaptation there was a very great increase in relative sensitivity between 557 and 697 mμ and a decrease between 557 and 454 mμ. Sloan points out the important bearing of her results on the technique of heterochromatic photometry and on the precautions which should be used for the control of state of adaptation in the work of the standardizing laboratories.

Also in 1928, Almack (56) published a quantitative study of chromatic adaptation, in which the loss of chromatic sensitivity for appropriately selected intervals of time was compared for several conditions of intensity, brightness and saturation of the stimuli under dark adaptation and under an adaptation to 214 ft.-c. of daylight illumination. The loss of chromatic sensitivity was measured by the threshold method. Of interest in relation to the present study is the fact that the first point of her adaptation curves represents for the non-fatigued eye the threshold values for the stimuli used. From these values, therefore, a direct comparison can be made of the chromatic threshold for central vision under conditions of light and dark adaptation. The following stimuli were used: red (670 mμ), yellow (579 mμ), green (515 mμ) and blue (466 mμ). The stimulus subtended a visual angle of 5° 44′. A stimulus of this magnitude was needed to provide an area sufficiently large for consistency of result in experiments in adaptation. The chromatic thresholds were measured in energy units. The ratios of these thresholds for light and dark adaptation for central vision, as computed from Almack's data, are, for red 1:13, for yellow 1:7, for green 1:21, and for blue 1:8.

The present study also furnishes a comparison of the effect of state of general adaptation on the chromatic sensitivity of the eye. In this study, moreover, the comparison can be made not only at the center of the field, but for some 60 or more points in the periphery. The comparison of the thresholds for color at various points in the peripheral field and at the limits of sensitivity is of particular interest and importance in view of the attempts that have been made to introduce dark-room perimetry in the study of

eye diseases. The two conditions of adaptation for which the chromatic sensitivity of the eye was determined were complete dark adaptation and light adaptation in which the eye was sensitized to 7 ft.-c. of illumination. The method of obtaining this illumination is given in detail on p. 61. The stimuli used were those described in the earlier sections of the study.

The results of this comparison are given in Figs. 47–50. The curves designated by the numeral (1) represent the chromatic sensitivity of the eye when completely dark-adapted; those designated by the numeral (2), the chromatic sensitivity at the same points for the eye adapted to 7 ft.-c. of illumination. Degrees of eccentricity in the field of vision are plotted along the abscissa. Sensitivity is plotted along the ordinate. In Figs. 47 and 48 the curves for the four colors at both states of adaptation are shown for the temporal and nasal quadrants of the 180° meridian; in Figs. 49 and 50, for the upper and lower quadrants of the 90° meridian.

In any comparison of the effect of state of adaptation on the chromatic response of the eye in the central and peripheral portions of the field, the difference in the range of change of adaptation from the center to the periphery should of course be kept in mind. That is, the range has its maximum value at the center where the retina receives direct illumination from the pupillary aperture, and its minimum value at the periphery where it always receives relatively low intensities of illumination. In passing from the center to the periphery, therefore, the process of adaptation begins at progressively lower levels.

In connection with the present study the following points of interest may be noted:

(1) The sensitivity of the dark-adapted eye to color is far in excess of that of the light-adapted eye within a radius of 30° from the center. At the center it is from 7–40 times greater, depending on the wave-length, and at 10°–30° from the center it is from 3–50 times greater.

(2) The increase in sensitivity of the dark-adapted as compared with that of the light-adapted eye at the center of the field is approximately 4 times greater for the blue and green than for

FIGURES 47–50. Curves showing the chromatic sensitivity of the eye to spectrum lights from center to periphery of the field in the 180° and 90° meridians under conditions of (1) dark adaptation and (2) adaptation to 7 ft.-c. of illumination.

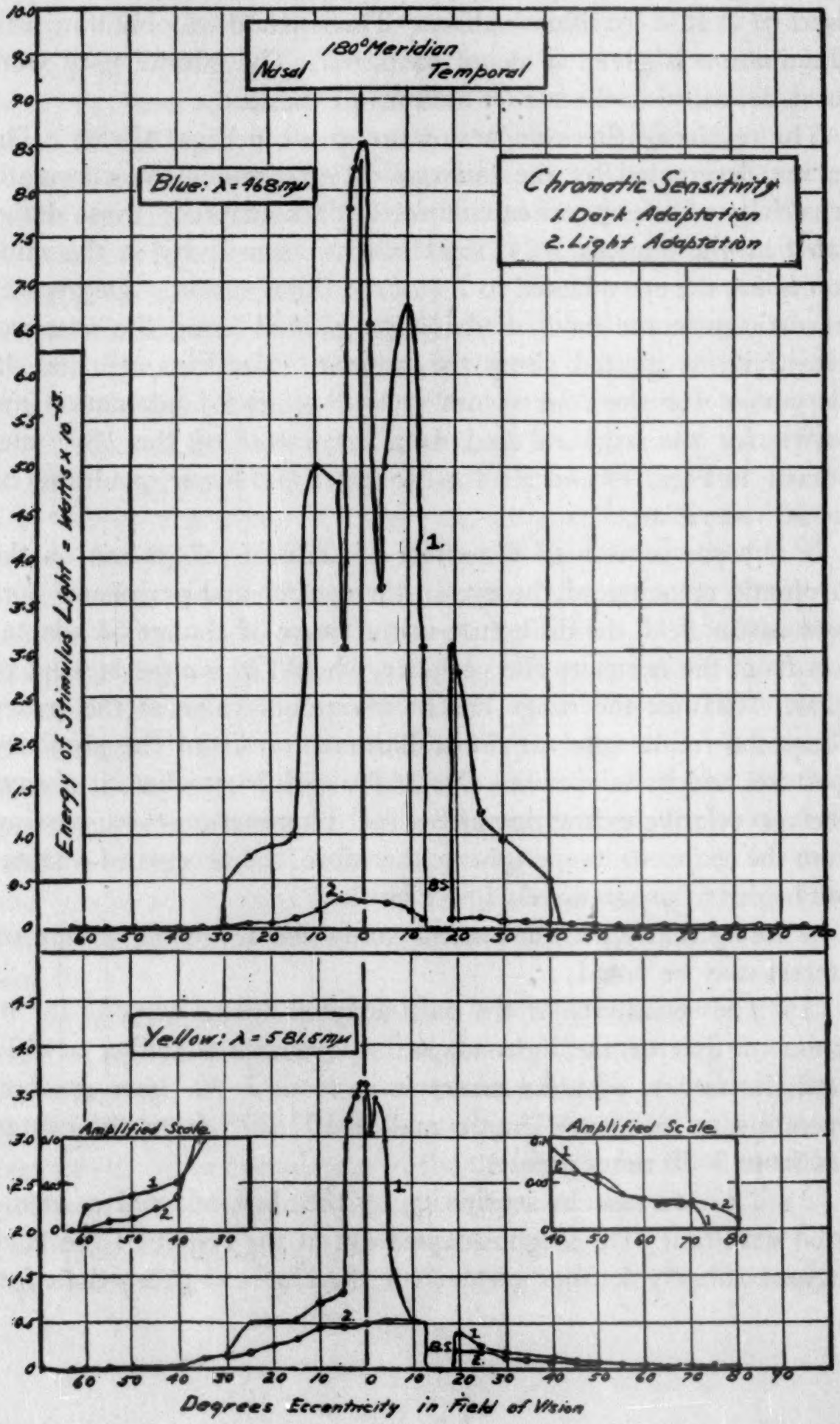


FIG. 47

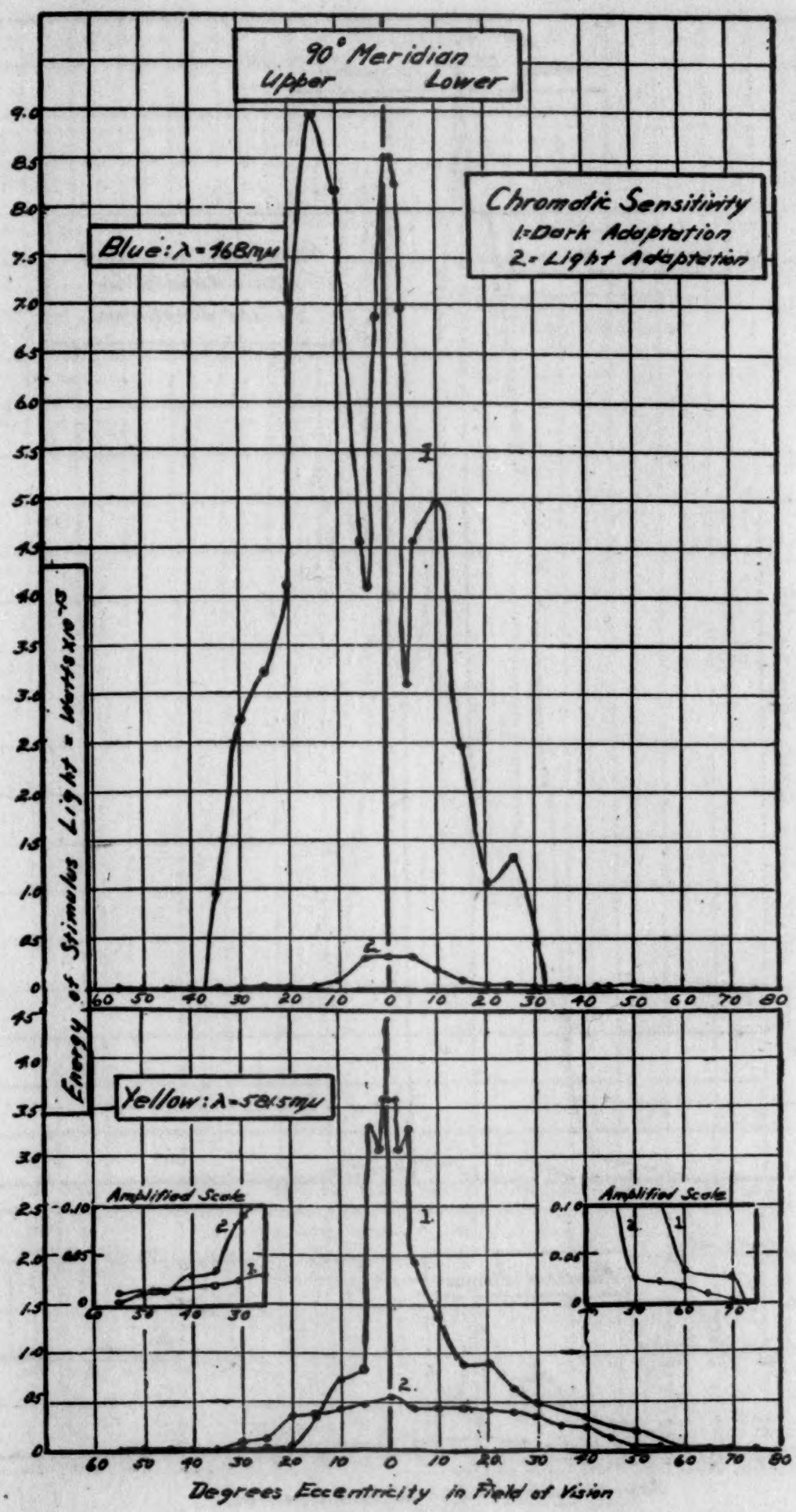

90° Meridian
Upper
Lower
Chromatic Sensitivity
1=Dark Adaptation
2=Light Adaptation
Blue: λ=468mμ
Yellow: λ=581.5mμ
Amplified Scale
Amplified Scale
Energy of Stimulus Light =
Degrees Eccentricity in Field of Vision

FIG. 48

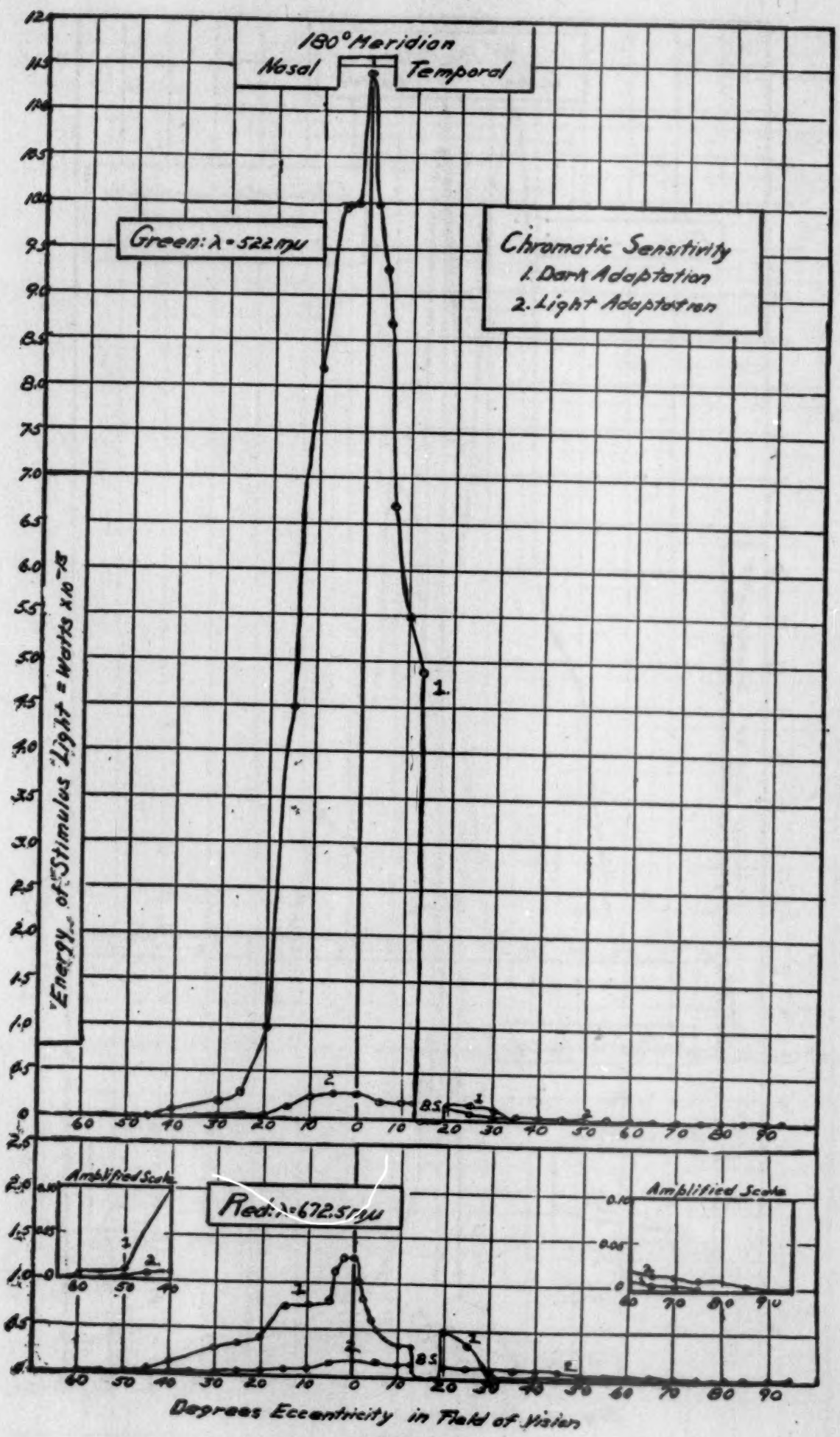

180° Meridion
Nasal
Temporal
Green: λ = 522 mμ
Chromatic Sensitivity
1. Dark Adaptation
2. Light Adaptation
Energy of Stimulus "Light" = Watts x 10⁻⁵
Amplified Scale
Degrees Eccentricity in Field of Vision

FIG. 49

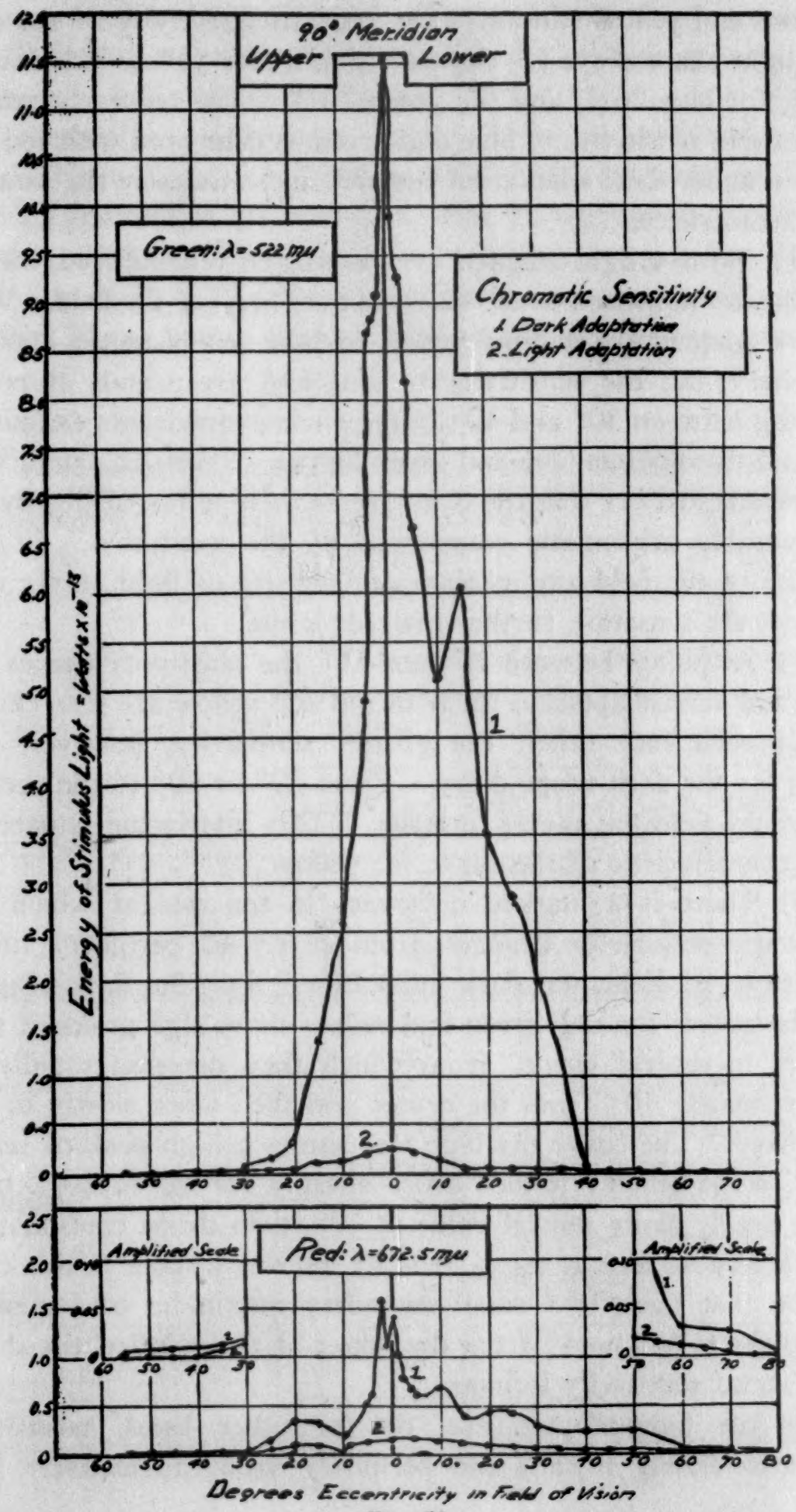

90° Meridian
Upper
Lower
Green: λ = 522 mμ
Chromatic Sensitivity
1. Dark Adaptation
2. Light Adaptation
Energy of Stimulus Light = bottle x 10⁻¹⁵
Red: λ = 672.5 mμ
Amplified Scale
Amplified Scale
Degrees Eccentricity in Field of Vision

FIG. 50

the red and yellow stimuli. The ratio of sensitivity of the dark and light-adapted eye for central vision is, for yellow 7:1, for red 10:1, for blue 26:1, and for green 40:1. The relatively greater increase in sensitivity to blue and green as compared with red and yellow under dark adaptation remains approximately the same to 30° eccentricity.

(3) With a light-adapted eye, it will be remembered, all the colors may be sensed to the extreme periphery of the field. With a dark-adapted eye red and yellow may be sensed to the extreme periphery, but the sensitivity to blue and green ends at points ranging between 30° and 40° in the various quadrants examined. Beyond these points blue and green lighten to such an extent with a dark-adapted eye that the color seems to be extinguished by the unfavorable achromatic component of the excitation. In this portion of the field any increase of intensity of light serves only to shift the sensation further towards white.

(4) At points between 30° and 60° the sensitivity curves for light and dark adaptation for both red and yellow are seen closely to approach each other, the greater sensitivity, however, still being for the dark-adapted eye. From 50° or 60° to the periphery of the field the curves interlace. This interlacing is particularly characteristic of the curve for yellow.

(5) There is a marked difference in the rate at which the chromatic sensitivity changes from center to periphery under conditions of light and dark adaptation. For the dark-adapted eye the curves for red, green and yellow show high peaks of sensitivity in central vision, from which they decrease rapidly to approximately 10° from the center and then more slowly to the periphery. The curve for blue also shows a high peak of sensitivity in the center; it then drops sharply for the first 4°, rises again nearly to its central value at 10°, then drops continuously and rapidly to zero at 30°. It is of interest to note in this connection that there is a small secondary maximum of increased sensitivity to yellow 4° from the center at the point of the sharp decrease of sensitivity to blue.

For the light-adapted eye, on the other hand, sensitivity decreases slowly toward the periphery from a relatively low

maximum value at the center. The result is a low, rounded, gently sloping curve in sharp contrast to the high narrow peak of the curves for the dark-adapted eye.

For example, as shown in Table 26, the sensitivity to yellow for the light-adapted eye between 0° and 10° decreases not more than 22 per cent in any meridian, with an average change of 10 per cent, while for the dark-adapted eye the corresponding change ranges from 50 to 80 per cent, with an average change of approximately 70 per cent. Further, the percentage decrease in sensi-

TABLE 26.

Showing the percentage decrease in sensitivity to spectrum lights in the temporal and nasal quadrants of the 180° meridian and the lower quadrants of the 90° meridian under conditions of light and dark adaptation (A) from 0–10° and (B) from 0–5°.

A.

Meridian	Percentage Decrease in Sensitivity from 0° to 10°.							
	Yellow		Blue		Green		Red	
	Light adapt.	Dark adapt.	Light adapt.	Dark adapt.	Light adapt.	Dark adapt.	Light adapt.	Dark adapt.
Temporal	0	50	47	22	29	52	14	28
Nasal	4	80	47	6	4	28	64	48
Upper	22	77	69	3	12	86	86	87
Lower	16	62	43	6	44	55	15	51

B.

Meridian	Percentage Decrease from 0° to 5°.		
	Blue		
	Light adapt.	Dark adapt.	
Temporal	7	42	
Nasal	6	44	
Upper	0	46	
Lower	0	64	

tivity for the dark-adapted eye as compared with the light-adapted eye is roughly from 4–50 times greater for yellow, varying with the quadrant considered; from 0–3 times greater for red; from 1–7 times greater for green. The average values of decrease in sensitivity for yellow, red and green are respectively 20, 2 and 4 times greater for the dark than for the light-adapted eye. The sensitivity to blue, on the other hand, shows a smaller percentage decrease for the light-adapted eye for this region of the field of vision, due to the occurrence of a second peak of sensitivity to blue in the curve at 10° for the dark-adapted eye. If, however, the interval from 0°–5° is considered, the percentage decrease is found to be from 6–64 times greater for the dark than for the light-adapted eye, and on the average 30 times greater. The percentage decrease would be still greater were the interval taken from 0°–4°. One could hardly desire a more striking demonstration than this of the fallacy involved in drawing conclusions as to the rate and manner of change in the sensitivity of the retina to color based on an examination at the center and limits of the field, or even at relatively remote points of the retina. The misconceptions that have been held in this connection and the very great importance of their bearing on clinic and laboratory methods and technique and on the conclusions that have been drawn for practical and theoretical purposes have been noted in an earlier chapter.

(6) Variations in sensitivity, particularly around the macula, are brought out more clearly with dark adaptation. This effect is especially noticeable for blue and yellow. As has already been shown, the increase in sensitivity to yellow at a point 4° from the center of the field is accompanied by a decrease in sensitivity to blue. Another example of this reversal of ratio of sensitivity to the paired colors is found at a point 10° from the center in the lower quadrant, where a sudden increase in sensitivity to red and a sharp decrease in sensitivity to green occur. No corresponding variations were observed when the eye was light-adapted.

(7) A comparison of results obtained by the writer at 7 ft.-c. of illumination and by Ferree and Rand (1) at 32 ft.-c. with the same spectrum stimuli shows for central vision an approximate

equality of sensitivity within the limits of individual variation; but for the mid periphery there is comparatively a much greater sensitivity at 7 ft.-c. From this fact and the results obtained by the writer under light and dark adaptation, it would not seem improbable to conclude that the chromatic sensitivity of the peripheral retina, at least within 30° or 40° of the center, increases with decrease in the illumination to which the eye is adapted.

That the illumination to which the eye is adapted is a prominent factor in the chromatic sensitivity of the retina is obvious from the foregoing results. This factor should then be included as one of those which have caused the variable and contradictory results obtained by different investigators. The results also bear directly on the attempts that have been made to introduce dark-room perimetry into diagnostic work. The results of this study clearly indicate that perimetry under dark and light adaptation cannot be used interchangeably. Perimetry under dark adaptation will have to be used either as a supplement or a substitute for perimetry under light adaptation. The former is scarcely feasible and the latter from the standpoint of range of serviceability and accomplishment is not desirable.

V. SUMMARY.

A comprehensive survey of the threshold sensitivity of the retina, both achromatic and chromatic, has been made from center to periphery in a number of meridians. The determinations have been quantitative as far as is possible in work of this type; that is, spectrum lights of a definite composition and purity have been used as stimuli and all measurements of the intensity of these stimuli have been made in terms of energy. This procedure is obviously essential if a comparison is to be made of the sensitivity of the retina to wave-length at a given point or for a given wave-length from point to point in the same or in different meridians.

In order to ascertain the effect of state of adaptation on chromatic sensitivity, the chromatic thresholds have been determined under light and dark adaptation. For the work in light adaptation the intensity of illumination used was that which has been adopted as standard in the clinic practice of perimetry:—7 ft.-c. A careful control was exercised of all the variable factors which have been found to influence the chromatic response from center to periphery of the field. The influence of brightness of preexposure and surrounding field, for example, was eliminated by using in every case a preexposure surface and surrounding field of the brightness of the stimulus at threshold intensity at the point in the field for which the threshold was determined.

The achromatic thresholds were determined with a completely dark-adapted eye at the same points in the field as were used for the chromatic thresholds. From a comparison of these two sets of threshold values, it has been possible to designate for the first time in an absolute scale of intensities for all the stimuli used and points examined, the value of the photochromatic interval. This marks the limits of the first important qualitative change in the retina's reaction to intensity of spectrum light.

Especial attention has been given also to the variations in the light and color sensitivity of the dark-adapted eye in and around the macula. This, it scarcely need be noted, has an important bearing on systematic and theoretical interests.

The size of stimulus used throughout subtended a visual angle of 1°16′, a size which would fall, according to the measurements given by Parsons and others, within the rod-free area of the fovea. When working in the light room an adaptation period of 30 minutes was given. In the dark room a period of 45 minutes was found to be sufficient for complete dark adaptation. The spectrum lights used as stimuli were freed from residual impurities by the use of filters specially selected for this purpose, and the energy of these stimuli was measured both at the analyzing slit of the spectroscope and at the eye by means of a bismuth-silver thermopile and a Thomson galvanometer designed for use with this thermopile.

The results of the experiments carried out under the above conditions may be summarized as follows:[1]

I. With Light Adaptation (Preexposure and Surrounding Field of a Gray of the Brightness of the Stimulus).

1. There was wide variation in the chromatic sensitivity to a given range of wave-lengths from center to periphery in the same meridian. The sensitivity to yellow, for example, was found to be in the different quadrants from 276 to 5170 times as great at the center as at the periphery; for green this range of

[1] While the use of more than one observer in these experiments was precluded by the range of work covered, validity of result was secured not only through the standardization and control of all factors known to influence the sensitivity of the retina to color but also through careful tests of the normality of the observer as to acuity, light and color sensitivity and visual fields and of the characteristics of peripheral refraction of the eye employed. In so far, then, as the eye used in the investigation may be regarded as representative of the normal eye, and with due regard to individual variation, the conclusions drawn may be considered to have a general application. In this connection, the relation of the results of the present study to those previously obtained in the series of investigations of the sensitivity of the eye to color conducted by Ferree and Rand should be borne in mind.

ratios varied in the different quadrants from 40 to 2443; for blue, from 659 to 3298; and for red from 728 to 4885.

2. Great irregularities occurred in the ratio of sensitivity from point to point for a given color in the same meridional quadrant and at corresponding points in different quadrants.

3. Great irregularities occurred also in the ratios of sensitivity to the different colors from point to point in a given meridional quadrant and at corresponding points in different meridional quadrants. Particularly notable among these anomalies of relationship are the small regions of decreased sensitivity to one color with no loss of sensitivity to the other colors. In some quadrants the depression in sensitivity amounts almost to complete blindness to color. For the eye under investigation they were found to be greatest in frequency and magnitude for the blue stimulus. The recurrence of such anomalies in the normal eye is of interest and importance both in relation to theory and to the uses that are made of the study of the visual field in the diagnosis of disease.

4. With a high intensity of stimulus of the size used (1° 16′) the limits of chromatic sensitivity to yellow were found to be coextensive with those for white light vision. This was also true for red except in the upper temporal quadrant beyond 90° where it appeared as yellow, and for blue except in the temporal and lower temporal quadrants beyond 95° where it appeared as white. The limits for green fell inside the limits for red and blue in the temporal and lower nasal quadrants.

5. With stimuli of equal energy for all but very high intensities an interlacing or crisscrossing of limits was found for red, blue and green. At all intensities with stimuli equalized in energy, the limits for yellow fell outside those for red, blue and green. The interlacing of limits for red, blue and green is thus not necessarily a pathological phenomenon as was formerly believed by diagnosticians. It is, rather, a characteristic relationship for the normal eye when stimuli of the same or nearly the same physical intensity are used, and is due to the wide variations in the ratio of sensitivity to the colors in question from quadrant to quadrant of the different meridians.

6. Contractions of the field, changes in the shape of the field, and reversals in the order of ranking as to the breadth of the field also are not necessarily pathological phenomena. All may be produced for the normal eye by varying any of the factors which strongly affect the retina's response to color. Changes in size of field from very narrow to very wide may be produced by varying either the size or the intensity of the stimulus. Changes of shape are a corollary of change of size, due to the unequal change in sensitivity to a given color from center to periphery in the different meridional quadrants. Reversals of order of ranking as to breadth of field also follow wide variations in size due to the reversal in the ratios of sensitivity to the different colors which are found to occur in passing from the center to the periphery of the field. Extensive variations in size, shape and relationship of the fields not only may be produced by varying the factors which influence the chromatic response of the retina, but will take place as a normal result of variations in conditions which occur from time to time and from place to place in the practice of perimetry unless great care is exercised as to standardization and control.

7. A general tendency was found for the area of the color fields to vary with the logarithm of the intensity of the stimulus light.

8. A comparison of the limits obtained at the various levels of intensity with those obtained under similar experimental conditions and with the same observer for the standard pigment papers of the Heidelberg series on the Ferree-Rand perimeter, shows that the effective intensity of a 1° stimulus of the red and blue of this series corresponds closely to an energy value of 100 watts $\times 10^{-13}$ for the spectrum stimuli; that of the green to an energy value of 50 watts $\times 10^{-13}$. From a consideration of the relative intensities of these stimuli the order of ranking as to breadth of field obtained with the Ferree-Rand perimeter can also readily be understood, *i.e.*, the field for green is the narrowest and the limits for red and blue interlace. The reason for the traditional ranking of the fields from widest to narrowest in the order of blue, red, and green may also be inferred from a consideration of the relative intensities of these stimuli and other data presented in

this study. The intensities of the pigment stimuli used with the older perimeters were in all probability in the order from highest to lowest intensity, blue, red, and green.

The pigment stimuli, it will be noted, are of comparatively low intensity. It should be obvious that stimuli of this order of intensity can not bring out comprehensively the true characteristics of the retina's response to color, yet many assertions as to the characteristics of retinal response and points of color theory have been based on explorations of the retina with stimuli of this order of intensity.

9. Changes in comparative sensitivity to the different colors were found to sustain an interesting relationship to the hue changes of the red and green stimuli. That is, at those points where a loss of sensitivity occurs to one of these colors relative to that for yellow, a change of hue towards yellow is found for that color. This is explained on the ground that red and green stimuli also arouse a weak yellow excitation which is subliminal if the red or green sensation is strong. Towards the periphery, however, where the sensitivity to red and green decreases more rapidly than that to yellow, or at other points where a relative decrease in sensitivity to one or the other of these colors relative to that for yellow occurs, the yellow excitation rises above the threshold of sensation and is seen in combination with the red or green.

II. With Dark Adaptation.

A. Chromatic Sensitivity.

1. With the dark-adapted eye chromatic sensitivity was found to be greatest for all colors at the fovea. It decreases rapidly for the first few degrees, then more gradually towards the periphery.

2. Color sensitivity was found not to extend to the periphery for all wave-lengths. It ended for blue and green at points ranging from 30°–40° from the fovea. Beyond these points any increase in intensity served only to change the achromatic component of the sensation towards white. Yellow, on the other hand, was seen to the periphery in the nasal quadrants and as far as

80° in the temporal quadrants. Sensitivity to red extended to the extreme periphery in all quadrants.

3. Great irregularity in the ratio of sensitivity to the different colors occurred from point to point in the same meridional quadrant and at corresponding points in the different quadrants.

4. A marked decrease in sensitivity to blue was found at 4° from the center in all meridional quadrants. An increase in sensitivity to yellow was found at the same point. A photograph of the fundus shows a strong macular reflex at a corresponding distance from the fovea. The possibility of a greater density in the yellow pigmentation of the macula at this point is suggested in explanation of these results.

5. A tendency was was found for the maximum chromatic sensitivity of the retina to wave-length to shift from the shorter to the longer wave-lengths in passing from the center to the periphery of the field. That is, from 0° to 10° or 15° the maximum was in the green; from 10° or 15° to 30° or 40°, in the blue; from 30° or 40° to 70° or 80°, in the yellow; and from 70° or 80° to the periphery, in the red.

B. Achromatic Sensitivity.

1. The lowest achromatic sensitivity to all wave-lengths was found at the fovea; the highest at points ranging from 30°–50° from the fovea, varying with the color and the quadrant investigated. From these points to the periphery there was a comparatively small decrease in sensitivity. Within the first 5° of the fovea the increase was very rapid. The amount of this increase, averaged for the four quadrants investigated, was for the red, yellow, green and blue, respectively, 2.18, 12.52, 22.64 and 6.51 times the central sensitivity.

2. The retina was found to be most sensitive to green at every point investigated. The ranking as to sensitivity from highest to lowest was, in general, green, yellow, blue, red. Exceptions to this ranking were found at the fovea and at a point 5° from the fovea in the nasal quadrant. At these points the sensitivity to blue was greater than to yellow.

3. The point of maximum achromatic sensitivity for the stimuli used was at 40° in the nasal quadrant. At this point the value of the minimum visible for the green was 0.81 watts x 10^{-16}.

C. *The Photochromatic Interval.*

1. With a dark-adapted eye a photochromatic interval was found for all the colors in all parts of the field. At the center the interval for red was very small. The ranking for the other colors from greatest to least was yellow, blue, green. At points 1°–2° from the center, however, the ranking for red shifts from minimum to maximum. At the center of the field the values of the interval for red, yellow, green and blue were, respectively, 0.039, 0.127, 0.043 and 0.065 watts x 10^{-13}.

2. The interval was smallest at the center of the field for all of the stimuli used. The increase from center to periphery was very great for all the quadrants investigated, as might be expected from the rapid loss of chromatic sensitivity from center to periphery of the field and the comparatively small change in achromatic sensitivity. For red the values of the interval ranged from 0.039 watts x 10^{-13} at the center to 107.7–288.4 watts x 10^{-13} at the periphery; for yellow, from 0.127 watts x 10^{-13} at the center to 35–77.87 watts x 10^{-13} at the periphery; for green, from 0.043 watts x 10^{-13} at the center to 7.84–11.47 watts x 10^{-13} at the periphery; and for blue, from 0.065 watts x 10^{-13} at the center to 1.03–2.16 watts x 10^{-13} at the periphery.

3. The relation of magnitude of interval to wave-length varied irregularly from point to point in a given meridional quadrant and at corresponding points in the different quadrants. In general at the center of the field red was found to have the smallest value of interval; from 1°–10°, varying with the quadrant examined, there was a shift to green; from 10°–30°, to blue; from 30°–80°, to yellow; and from 80°–90°, back again to red.

4. The ranking as to rapidity of increase in the size of the interval from center to periphery was from greatest to least, red, yellow, green and blue.

III. Effect of State of Adaptation of the Eye on Chromatic Sensitivity.

1. The sensitivity of the dark-adapted eye to color was found to be far in excess of that of the light-adapted eye within a radius of 30° from the center. At the center it was from 7–40 times greater, depending upon the color, and from 10°–30° it was from 3–50 times greater. Between 30° and 40° sensitivity to blue and green ends. The sensitivity to yellow and red remained slightly greater for the dark-adapted eye to 50°–60°. From these points to the periphery the sensitivity to red and yellow was approximately the same for both states of adaptation.

2. There was a marked difference in the rate of change of sensitivity to the different colors from center to periphery of the field in a given meridional quadrant for the two states of adaptation. For example, from 0°–10° the sensitivity to yellow under dark adaptation decreased from 50–80 per cent, depending upon the quadrant examined, with an average change of 70 per cent; under light adaptation the corresponding decrease was not more than 22 per cent in any quadrant, with an average change of 10 per cent. The percentage decrease in sensitivity to yellow in this region was from 4–50 times greater for the dark than for the light-adapted eye; for red from 0–3 times greater; and for green 1–7 times greater. For blue from 0°–5° it was from 6–64 times greater. From 0°–10°, however, the percentage decrease was slightly greater for the light than for the dark-adapted eye in case of this color, as the result of a secondary peak of sensitivity which was found at eccentricity of 10° for the dark-adapted eye.

3. The increase in sensitivity at the fovea of the dark as compared with the light-adapted eye was approximately 4 times greater for blue and green than for red and yellow. This relationship holds to an eccentricity of 30° or 40°, where the sensitivity of the dark-adapted eye to blue and green ends.

4. Variations in chromatic sensitivity in and about the macula were more clearly brought out with the dark than with the light-adapted eye.

No significant attempt has been made to relate these results to

existing color theories. It may be pointed out, however, that irregularity of ratio of sensitivity from point to point in a given meridional quadrant and at corresponding points in the different quadrants, and an interlacing of the limits of color sensitivity are found to be typical of the pairs of colors rather than constancy of ratio from center to periphery and coincidence of limits, as has been claimed by some of the followers of the paired process theories; also that the irregularity of ratio of sensitivity from point to point in the same meridional quadrant and at corresponding points in the different quadrants makes the possibility of obtaining stable colors, *i.e.*, colors which remain the same in hue from center to periphery, to say the least, very remote. It is also interesting to note that while the ratios of sensitivity to the complementary colors vary widely from point to point from the center to the periphery of the field, the cancelling proportions of these colors have been found to remain constant, or nearly so.

Irregularity and incompleteness of development of function are of course what might be expected in the peripheral retina from its conditions of use and the service which it is called upon to render. The actual picture, however, is very different from the traditional one drawn to the scale and pattern of theoretical and systematic thinking. What takes place theoretically is of comparatively little importance, but it is extremely needful to know the actual situation for the practical applications which are found for the study and testing of the visual field.

BIBLIOGRAPHY

Historical Summary

1. Ferree, C. E., and Rand, G. Chromatic Thresholds of Sensation from Center to Periphery of the Retina and Their Bearing on Color Theory. *Psychol. Rev.*, 1919, **26**, 16–41.
2. Ferree, C. E., and Rand, G. Chromatic Thresholds of Sensation from Center to Periphery of the Retina and Their Bearing on Color Theory. *Psychol. Rev.*, 1919, **26**, 150–163.
3. Mariotte. *Philos. Trans.*, 1668, **3**, 668; 1670, **5**, 1023–1042.
4. Young, T. On the Mechanism of the Eye. *Philos. Trans.*, 1801, **92**, 23 ff; *Miscellaneous Works of Thomas Young.* London: 1855, 12 ff.
5. Troxler, D. Ueber das Verschwinden gegebener Gegenstände innerhalb unseres Gesichtskreises. *Ophth. Bibliothek herausgegeben von Himly u. Schmidt*, Jena, 1804, **1**, 1–53.

6. PURKINJE, J. E. Beobachtung und Versuche zur Physiologie der Sinne. *Beiträge zur Kenntniss des Sehens,* 1823, 1, 76; 1825, 2, 14.
7. FERREE, C. E., and RAND, G. A Note on the Determination of the Retina's Sensitivity to Colored Light in Terms of Radiometric Units. *Amer. J. Psychol.,* 1912, 23, 328–332.

BRIGHTNESS OF PREEXPOSURE AND SURROUNDING FIELD

8. KRÜKOW. Objective Farbenempfindung auf den peripherischen Theilen der Netzhaut. *Arch. f. Ophth.,* 1874, 20(1), 255–296.
9. WOINOW, M. Zur Farbenempfindung. *Arch. f. Ophth.,* 1870, 16, 219.
10. AUBERT, H. *Physiologische Optik.* Leipzig: 1876, 541–544.
11. FERNALD, G. M., The Effect of Achromatic Conditions on the Color Phenomena of Peripheral Vision. *Psychol. Monog.,* 1909, 10(3), No. 42.
12. HESS, C. Ueber den Farbensinn bei indirectem Sehen. *Arch. f. Ophth.,* 1889, 35, 1–62.
13. TSCHERMAK, A. Beobachtungen über die relative Farbenblindheit in indirectem Sehen. *Arch. f. Physiol.* (Pflüger), 1890, 82, 559–561.
14. RAND, G. The Factors that Influence the Sensitivity of the Retina to Color: A Quantitative Study and Methods of Standardizing. *Psychol. Monog.,* 1913, 15(1), No. 62.
15. FERREE, C. E., and RAND, G. The Limits of Color Sensitivity: Effect of Brightness of Preexposure and Surrounding field. *Psychol. Rev.,* 1920, 27, 377–398.
16. FERREE, C. E., and RAND, G. Effect of Brightness of Preexposure and Surrounding Field on Breadth and Shape of the Color Fields for Stimuli of Different Sizes. *Amer. J. Ophth.,* 1924, 7, 843–850.
17. FERREE, C. E., and RAND, G. An Illuminated Perimeter with Campimeter Features. *Amer. J. Ophth.,* 1922, 5, 455–465; A New Laboratory and Clinic Perimeter. *J. Exper. Psychol.,* 1922, 5, 46–67.
18. FERREE, C. E., RAND, G., and WENTWORTH, H. A. The Blind Spot for Achromatic and Chromatic Stimuli. *Amer. J. Ophth.,* 1925, 8, 620–625.

INTENSITY OF THE GENERAL ILLUMINATION

19. THOMPSON, H. B., and GORDON, K. A. A Study of After-Images on the Peripheral Retina. *Psychol. Rev.,* 1907, 14, 122–167.
20. KRAMER, J. Untersuchen über die Abhängigkeit der Farbenempfindung von der Art und dem Grade der Beleuchtung. *Inaug. Diss., Marburg,* 1882.
21. WOLFFBERG, L. Ueber die Prüfung des Lichsinnes. *Arch. f. Ophth.,* 1885, 31, 1–78.
22. RAND, G. The Effect of Changes of the General Illumination of the Retina Upon Its Sensitivity to Color. *Psychol. Rev.,* 1912, 19, 463–490.
23. FERREE, C. E., and RAND, G. The Effect of Variations of the Intensity of the Illumination on the Perimeter Arm on the Determination of the Color Fields. *Psychol. Rev.,* 1922, 29, 457–473.

TIME OF EXPOSURE OF THE STIMULUS

24. BACON, F. *Novum Organum,* 1711, lib. ii. Äph. xlvi.
25. BEUDANT. Essai d'un Cours Elementaire et Général des Sciences Physiques; *Partie Physique,* 1815, 480 de la 3me ed.

26. PLATEAU. *Nouveaux Memoires de l'Academie Royale des Sciences et Belles Lettres de Bruxelles,* 1834, **8**, 53.
27. SWAN, W. On the Gradual Production of Luminous Impressions on the Eye and Other Phenomena of Vision. *Trans. Roy. Soc. Edin.,* 1849, **16**, 581–603.
28. EXNER, S. Über die zu einer Gesichtswahrnehmung nöthige Zeit. *Sitzungsberichte der Kaiserlichen Akademie der Wissenschaften,* 1868, **58**, 601–631.
29. CHARPENTIER, A. Recherches sur la persistance des impressions rétiniennes et sur les excitations lumineuses de courte durée. *Arch. d'Ophth.,* 1890, **10**, 108–135.
30. LOUGH, J. E. The Relations of Intensity to Duration of Stimulation in Our Sensations of Light. *Psychol. Rev.,* 1896, **3**, 484–492.
31. BROCA, A., and SULZER, D. Les fonctions rétiniennes en fonction du temps. *Ann. d'Ocul.,* 1904, **131**, 279–286; La sensation lumineuse en fonction du temps pour les lumières colorées. *J. d'Physiol.,* 1904, **6**, 55–68; also *Comptes Rendus des Séances de l'Académie des Sciences,* 1903, **137**, 944–979.
32. MARTIUS, G. Über die Dauer der Lichtempfindungen. *Beitr. Psychol. u. Philos.,* 1905, **1**, 275–366.
33. BÜCHNER, M. Über das Ansteigen der Helligkeitserregung. *Psychol. Stud.,* 1906–1907, **2**, 1–29.
34. BERLINER, B. Der Ansteig der reinen Farbenerregung in Sehorgan. *Physiol. Stud.,* 1907, **3**, 91–155.
35. LAMANSKY, S. Über die Grenzen der Empfindlichkeit des Auges für Spectralfarben. *Arch. f. Ophth.,* 1871, **17**, 123–132.
36. KUNKEL, A. Über die Abhängigkeit der Farbenempfindung von der Zeit. *Arch. f. Physiol.* (Pflüger), 1874, **9**, 197–220.
37. DÜRR, E. Über das Ansteigen der Netzhauterregungen. *Wundt Philos. Stud.,* 1901–1903, **18**, 215–273.
38. MACDOUGALL, W. The Variations of the Intensity of Visual Sensations With the Duration of the Stimulus. *Brit. J. Psychol.,* 1904, **1**, 151–189.
39. BILLS, M. A. The Lag of Visual Sensation in Its Relation to Wave-Lengths and Intensity of Light. *Psychol. Monog.,* 1920, **28**(5), No. 127.
40. FERREE, C. E., and RAND, G. Flicker Photometry, II: Comparative Studies of Equality of Brightness and Flicker Photometry With Special Reference to the Lag of Visual Sensation. *Trans. Illum. Eng. Soc.,* 1923, **18**, 174–207.
41. PLATEAU. Ueber das Phänomen der zufälligen Farben. *Pogg. Ann. der Phys.,* 1834, **32**, 543–554.
42. BOKOWA, M. Ein Vernahren, künstliche Farbenblindheit hervorzubringen. *Zeit. f. rationelle Med.,* 1863, III Reihe, **17**, 161–165.
43. AUBERT, H. *Physiologische Optik.* Leipzig: 1876, 557.
44. BURCH, G. J. On Artificial Temporary Colour-Blindness With an Examination of the Colour Sensations of 109 Persons. *Proc. Roy. Soc., Lond.,* 1898, **63**, 35–38; *Philos. Trans.,* 1899, B, **191**, 1–35; Production of Artificial Colour-Blindness by Moonlight. *Proc. Roy. Soc., Lond.,* 1899–1900, **66**, 216–219.
45. BECK, A. Ueber künstlich hervorgerufene Farbenblindheit. *Arch. f. d. ges. Physiol.,* 1899, **76**, 634–640.

46. PORTER, A. W., and EDRIDGE-GREEN, F. W. Negative After-Images and Successive Contrast With Pure Spectral Colours. *Proc. Roy. Soc., Lond.*, 1912, B, **85**, 434–439.
47. EDRIDGE-GREEN, F. W. Color Adaptation. *Proc. Roy Soc., Lond.*, 1912–13, **86**, 110–114.
48. BRÜCKNER, v. A. Ueber die Sättigunssänderungen von Pigmentfarben durch Ermüdung der Netzhaut mit farbig wirkenden Lichte. *Arch. f. Augenhk.*, 1919, **85**, 12–27.
49. SHEPPARD, H. Foveal Adaptation to Color. *Amer. J. Psychol.*, 1920, 31, 34–58.
50. TROLAND, L. T. The Color Produced by Equilibrium Photopic Adaptation. *J. Exper. Psychol.*, 1921, **4**, 344–390.
51. SSAMUJLOW. Zur Frage der Ermüdung der Netzhaut durch verschiedene Farben (Roth, Grün, Blau). *St. Petersburger Med. Wochenschr.*, 1889, No. 3, III *Congress der russischen Aertze zu St. Petersburg*, 26.
52. EXNER, S. Ueber einige neue subjective Gesichtserscheinungen. *Arch. f. Physiol.* (Pflüger), 1868, **1**, 375–394.
53. HESS, C. Ueber die Tonänderungen der Spectralfarben durch Ermüdung der Netzhaut mit homogenem Lichte. *v. Graef. Arch. f. Ophth.*, 1890, **36**, (1), 1–33.
54. VOESTE, H. Messende Versuche über die Qualitätsänderungen der Spectralfarben in Folge von Ermüdung der Netzhaut. *Zsch. f. Psychol. u. Physiol. du Sinnesorg.*, 1898, **18**, 257–267.
55. SCHÖN, W. Einfluss der Ermüdung auf die Farbenempfindung. *v. Graef. Arch. f. Ophth.*, 1874, 20(2), 273–286.
56. ALMACK, M. R. A Quantitative Study of Chromatic Adaptation. *Psychol. Monog.*, 1928, **38**(2), No. 174.

SIZE OF STIMULUS

57. HUECK, A. Von den Grenzen des Sehensvermögens. *Müller's Arch.*, 1840, 95.
58. AUBERT, H. *Physiologie der Netzhaut.* Breslau: 1865, 121.
59. RAEHLMANN, E. Ueber Farbenempfindung in den peripherischen Netzhautpartien in Bezug auf normale und pathologische Brechungsstände. *Inaug. Diss.*, Halle, 1872.
60. SCHÖN, W. Ueber die Grenzen der Farbenempfindung in pathologische Fällen. *Klin. Monatsbl. f. Augenhk.*, 1873, 171.
61. SCHIRMER, R. Ueber erworbene und angeborene Anomalien des Farbensinns. *Arch. f. Ophth.*, 1873, **19**, 194.
62. BRIESEWITZ. Ueber das Farbensehen bei normalem und atropishem Nervus Opticus. *Inaug. Diss.*, Greifswald, 1873.
63. TSCHERMAK, A. Beobachtungen über die relative Farbenblindheit in indirectem Sehen. *Arch. f. Physiol.* (Pflüger), 1890, **82**, 559–560.
64. KIRSCHMANN, A. Die Farbenempfindung bei indirectem Sehen. *Philos. Stud.*, 1893, **8**, 612–613.
65. ABNEY, W. DEW. The Sensitiveness of the Retina to Light and Colour. *Philos. Trans.*, 1897, A, **190**, 169–171.
66. FERREE, C. E., and RAND, G. Effect of Size of Stimulus on Size and Shape of Color Fields. *Amer. J. Ophth.*, 1927, **10**, 399–411.
67. BULL, O. Studien über Lichsinn und Farbensinn. *Arch. f. Ophth.*, 1881, **27**, 54–154.

68. Hegg, E. Zur Farbenperimetrie. *Arch. f. Ophth.*, 1892, **38**, 145–168.
69. Aubert, H. *Physiologie der Netzhaut.* Breslau, 1865, 112.
70. Baird, J. W. *The Color Sensitivity of the Peripheral Retina.* Carnegie Institution of Washington, 1905.
71. Hess, C. Ueber den Farbensinn bei indirectem Sehen. *Arch. f. Ophth.*, 1889, **35**, 1–62.
72. Engelking, E., and Eckstein, A. Neue Farbenobjekte für die klinische Perimetrie. *Klin. Monatsbl. f. Augenhk.*, 1920, **64**, 664.

Intensity of Stimulus

73. Purkinje, J. Beobachtung und Versuche zur Physiologie der Sinne. *Beiträge zur Kenntniss des Sehens,* 1825, **2**, 109.
74. Landolt und Snellen. Ophthalmometrologie. *Handbuch der ges Augenheilk. von Graefe und Saemische,* 1874, **3**, 70; *Klin. Monatsbl. f. Augenhk.*, 1873, **11**, 376–377; *Ann. d'Ocul.*, 1874, **71**, 44–46.
75. Ferree, C. E., and Rand, G. The Absolute Limits of Color Sensitivity and the Effect of Intensity of Light on the Apparent Limits. *Psychol. Rev.*, 1920, **27**, 1–23.
76. Kirschmann, A. Die Farbenempfindung bei indirectem Sehen. *Philos. Stud.*, 1893, **8**, 562–614.
77. Chodin, A. Ueber die Empfindlichkeit für Farben in der Peripherie der Netzhaut. *Arch. f. Ophth.*, 1877, **23**, 177–208.
78. Raehlmann, E. Ueber Schwellenwerte der verschiedenen Spectralfarben an verschiedenen Stellen der Netzhaut. *Arch. f. Ophth.*, 1874, **20**, 232–254.
79. Butz, R. Vorläufige Mittheilungen über Untersuchungen der physiologischen Functionen der Peripherie der Netzhaut. *Arch. f. Anat. u. Physiol.*, 1881, 437–445.

Apparatus and Procedure

80. Ferree, C. E., and Rand, G. A Spectroscopic Apparatus for the Investigation of the Color Sensitivity of the Retina, Central and Peripheral. *J. Exper. Psychol.*, 1916. **1**(3), 247–283; Radiometric Apparatus for Use in Psychological and Physiological Optics. *Psychol. Monog.*, 1917, **24**, No. 103.
81. Monroe, M. M., The Energy Value of the Minimum Visible Chromatic and Achromatic for Different Wave-Lengths of the Spectrum. *Psychol. Monog.*, 1925, **34**(5), No. 158.
82. Sloan, L. L. The Effect of Intensity of Light, State of Adaptation of the Eye, and Size of Photometric Field on the Visibility Curve. A Study of the Purkinje Phenomena. *Psychol. Monog.*, 1928, **38**(1), No. 173.

Achromatic Thresholds

83. Ebert, H. Ueber den Einfluss der Schwellenwerthe der Lichtempfindung auf den Charakter der Spectra. *Ann. d. Phys.*, 1888, ser. 3, **33**, 136–158.
84. Pflüger, A. Ueber die Farbenempfindlichkeit des Auges. *Ann. der Phys.*, 1902, ser. 4, **9**, 185–208.
85. Wien, M. *Diss.*, Berlin, 1888; Ueber die Messung der Tonstärke. *Ann. der Phys.*, 1889, ser. 3, **36**, 834–857.
86. Drude, P. *Lehrbuch der optik.* Leipzig, 1900, 444 (2nd ed., p. 471).

87. Ives, H. The Minimum Radiation Visually Perceptible. *Astrophys. J.*, 1916, **44**, 124–127.
88. Russell, H. N. The Minimum Radiation Visually Perceptible. *Astrophys. J.*, 1917, **45**, 60–64.
89. Buisson, H. The Minimum Radiation Visually Perceptible. *Astrophys. J.*, 1917, **46**, 296–297.
90. Reeves, P. The Minimum Radiation Visually Perceptible. *Astrophys. J.*, 1917, **46**, 167–174.
91. Coblentz, W. W. Relative Sensibility of the Average Eye to Light of Different Colors and Some Practical Applications to Radiation Problems. Bureau of Standards, 1917, No. 303, 225.
92. v. Kries, J. (Breuer). Über die Absolute Empfindlichkeit der verschiedenen Netzhauttheile in dunkeladaptatierten Auge, I. *Zsch. f. Psych. u. Physiol. d. Sinnesorg.*, 1897, **16**, 327–336.
93. v. Kries, J. (Pertz, A.). Über die absolute Empfindlichkeit der verschiedenen Netzhauttheile in dunkeladaptatierten Auge, II. *Zsch. f. Psych. u. Physiol. d. Sinnessorg.*, 1897, **16**, 336–351.
94. v. Kries, J., and Eyster, H. Ueber die zur Erregung des Sehorgans erforderlichen Energiemengen. *Zsch. f. Sinnesphys.*, 1907, **41**, 373–394.
95. Abney, W. deW., and Watson, W. The Threshold of Vision for Different Coloured Lights. *Philos. Trans.*, 1916, A, **216**, 91–128.
96. Jones, Wynn. A Method of Measuring Nyctosis With Some Results. *Brit. J. Psychol.*, 1920–1921, **11**, 299–319.

Photochromatic Interval

97. Tschermak, E. Ueber der Bedeutung der Lichtstärke und des Zuständes des Sehorgans für farblose optische Gleichungen. *Arch. f. d. ges. Physiol.*, 1898, **80**, 297–328.
98. Fick, A. E. Studien über Licht und Farbenempfindung. *Arch. f. d. ges. Physiol.*, 1888, **43**, 441–501.
99. v. Kries, J., and Nagel, W. Ueber den Einfluss von Lichtstärke und Adaptation auf des Sehen des Dichromaten (Grünblinden). *Zsch. f. Psychol. u. Physiol. d. Sinnesorg.*, 1896, **12**, 1–38.
100. Hering, E. Ueber das sogenannte Purkinje'sche Phänomen. *Arch. f. d. ges. Physiol.*, 1895, **60**, 519–542.
101. Charpentier, A. *La Lumière et les Couleurs.* Paris, 1888, 213–216.
102. Abney, W. deW., and Festing, E. R. Colour photometry. *Philos. Trans. Roy. Soc., Lond.*, 1892, **183**, 531–567.

Effect of Adaptation

103. Nutting, P. G. Effects of Brightness and Contrast in Vision. *Trans. Illum. Eng. Soc.*, 1916, **11**, 939–946.
104. Ferree, C. E., Rand, G., and Buckley, D. A Study of Ocular Functions With Special Reference to the Lookout and Signal Service of the Navy. *J. Exper. Psychol.*, 1920, **3**, 347–356.

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